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Development of a Fibre Optic Weight Sensor for an On-board Aircraft Weight and Balance System

Summary Report

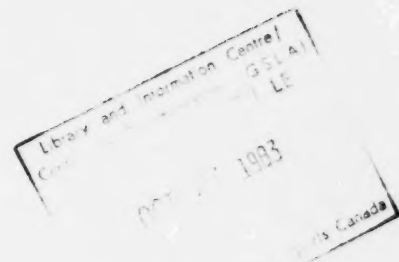
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DEVELOPMENT OF A FIBRE OPTIC
WEIGHT SENSOR FOR AN ON-BOARD AIRCRAFT
WEIGHT AND BALANCE SYSTEM



SUMMARY REPORT
prepared for
TRANSPORTATION DEVELOPMENT CENTRE
OF TRANSPORT CANADA

Egalement disponible en français

DSL DYNAMIC SCIENCES LIMITED
Montreal, Quebec

Report C162-05
February, 1983

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7 Author(s) R. Young, K.J.R. Mathewson, D.C. MacEachern				8 Transport Canada File No. D 1455-117-2	
9 Performing Organization Name and Address DSL DYNAMIC SCIENCES LIMITED 359, Ste-Croix Blvd., Suite 200 St-Laurent, Quebec H4N 2L3				10 DSS File No. 09SD.T8200-0-0543	
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15 Supplementary Notes Summary of "DEVELOPMENT OF A FIBRE OPTIC WEIGHT SENSOR FOR AN ON-BOARD AIRCRAFT WEIGHT AND BALANCE SYSTEM", TP 4367				16 TDC Project Officer W.H.D. Hanchet	
17 Abstract The report describes a fibre optic weight sensor designed, developed and demonstrated as an element for an on-board aircraft weight and balance system. The design meets general requirements for a sensor for any aircraft and specific requirements for the case study of the Canadair CL-600 Challenger. A prototype of the sensor was constructed and tested under controlled laboratory conditions to determine its response to load and temperature. The sensor demonstrated excellent vertical load measurement with high immunity to non-vertical loads. Experimental versions of two components produced some sensitivity to temperature and environmental disturbances; this sensitivity can be eliminated with proper components.					
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16 Agent de projet — CDT W.D. Hanchet		
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INTRODUCTION

An Aircraft Weight and Balance System (AWABS) provides on-board measurement and display of aircraft weight and centre of gravity under ground static conditions, independent of any system external to the aircraft. Such systems exist, but none has achieved the reliability and accuracy required to be employed as the primary load control system. Where used, they provide only an approximate check on the manual calculations performed on the ground. In addition, existing systems cannot be fitted to small transport aircraft.

Canadair's failure to locate a suitable AWABS supplier for its CL-600 Challenger aircraft kindled the interest of Transport Canada to further investigate the problem. Under contract on two previous AWABS projects, DSL Dynamic Sciences Limited demonstrated the feasibility of applying an interferometry technique using bonded optical fibres to measure deflections and hence the applied loads on aircraft axles, and that a practical design of a weight sensor utilizing this technique might be achievable. References 1 and 2 provide descriptions of these projects. Their results encouraged DSL to submit an unsolicited proposal to the Transportation Development Centre of Transport Canada (TDC) to initiate the development of a fibre optic weight sensor for use in an on-board AWABS. This document is a summary report of the ensuing project; the main report is available as Transport Canada report TP 4367 (ref. 3).

PROGRAM OBJECTIVE

The overall objective of the AWABS program is the development and production of on-board aircraft weight and balance systems to meet worldwide requirements.

PROJECT OBJECTIVE

The objective of this project was to design, develop and demonstrate a fibre optic weight sensor suitable for use as an element in an aircraft on-board weight and balance system.

The objective was to be achieved by developing a laboratory model of a weight sensor for a specific aircraft landing gear and demonstrating, under controlled laboratory conditions, that it could measure the vertical loads produced in the candidate landing gear.

PROJECT APPROACH AND ACTIVITIES

The approach taken to achieve the project objectives was to divide the project into two phases, separated by a design review.

In the first phase, general and specific requirements for the weight sensor were produced. A general requirements document, included in Reference 3, defined requirements for the sensor which are applicable to any commercial aircraft, and was based on a review of existing and proposed AWABS standards, and on comments provided by various aircraft manufacturers and operators. Specific requirements for the nose and main gear sensors were then established for the case study of the Canadair Challenger.

A design and analysis stage was then undertaken to establish the workability of the mechanical, optical, and electronic design concepts for the weight sensor. Significant activities in this stage included:

- A stress analysis using finite element modelling techniques of the case study nose gear axle with an installed sensor.
- The establishment of a design for the laboratory weight sensor comprising optical, mechanical, and electronic components.
- An estimation of the sensor outputs over the full range of loads applied to the axle.
- An error analysis identifying possible sources of error and their significance with respect to the accuracy requirements for the sensor.
- An investigation to determine the availability of the optical components suitable for in-aircraft application.
- Preparations for the design review.

To support the selected design and to demonstrate the viability of individual features of the sensor, various experiments were conducted; these included:

- A verification of the finite element modelling technique based on electrical strain gauge results of a loaded cylindrical axle and installed sensor.
- Investigations into optical fibre handling procedures.
- Construction and testing of an experimental electronic fringe counting circuit as a component of the sensor system.

The design review was held at DSL's plant on 18 August, 1982, and attended by representatives of TDC, the National Research Council, Canadair, de Havilland, and Air Canada. Achievements to date and the proposed approach for the balance of the project were reviewed and endorsed. It was agreed that the proposed design met the general and specific requirements, and a go-ahead was given for completion of the project as planned.

The second phase of the project consisted of the development and demonstration of a laboratory prototype of the approved design. Mechanical and optical components were procured, fabricated, and integrated with the electronic counter into the laboratory sensor. Because of their specialized nature, two of the optical components, namely, the splitter/coupler and fringe generator, could not be procured within the time and cost constraints for the project. (The difficulty was one of procurement rather than technical feasibility). Experimental versions of these two components were produced at DSL and used for the sensor. A test rig to apply loads and a temperature test chamber were also designed and fabricated.

Tests were performed by applying loads directly to the sensor, and to the sensor installed in a simulated axle. The purpose of the former was to establish the sensor's vertical load measurement characteristics (for example: sensitivity, linearity, repeatability, and immunity to non-vertical loads) without any external influences due to the mounting of the sensor. The purpose of the latter tests was to verify the predicted behaviour of the sensor when mounted in an axle. The response of the sensor due to temperature variations was also investigated to confirm theoretical predictions.

RESULTS

The results from the static load and temperature tests performed on the laboratory prototype optical weight sensor system are summarized below:

1. Generally, the system was found to meet the design objectives of measuring vertical load with little sensitivity to non-vertical loads.
2. The system demonstrated excellent vertical load measuring capability with high sensitivity and linearity, good repeatability, and no hysteresis.
3. Both the fringe count and strain gauge outputs showed good agreement with predicted values from the finite element analysis of the sensor tube.

4. Slight sensitivities to non-vertical loads were determined to be the result of the fibre winding and bonding procedures used, and can be eliminated with refined techniques.
5. No unexpected behaviour was initiated by installation of the transducer into the simulated axle. Deviations from theoretical behaviour are due to the elasticity of the connections between the sensor and axle.
6. Because of the "breadboard" arrangements for the splitter/coupler and fringe generator, the system was sensitive to temperature changes and to environmental disturbances such as acoustic noise and mechanical vibrations. With proper optical components these effects can be reduced to acceptable levels.
7. There is some sensitivity to temperature gradients along the sensor tube. However, due to the nature of the tests and the configuration of the prototype, the sensitivity of the bonded fibres could not be quantified.
8. The fringe pattern contrast was found to be affected by changes in load and in temperature due to changes in the state of light polarization in the two fibres.
9. After modifications were made to the electronic counter to account for the higher optical losses in the breadboard splitter/coupler, the counter provided an accurate and reliable measure of the fringe count. Errors in the electronic count only occurred due to the polarization effect described above.

CONCLUSIONS

In this project, a fibre optic weight sensor was designed and developed for use as an element in an on-board aircraft weight and balance system. A prototype version of the sensor was constructed and tested under controlled laboratory conditions. Specific conclusions resulting from this project are:

1. From a review of existing and proposed standards, and a survey of various aircraft manufacturers and operators, the SAE recommended practice ARP 1409 for an on-board aircraft weight and balance system was found to be an acceptable basis for the establishment of the "general requirements" document for an aircraft weight-sensing transducer.

2. The establishment of specific accuracy requirements for transducers for the nose and main gears of the case study has demonstrated that achievable transducer requirements can be defined to meet the overall system accuracy requirements of ARP 1409. The establishment of these requirements is a significant advance in the development of a sensor.
3. A design for the weight sensor comprising optical, mechanical, and electronic components has been achieved which meets the accuracy requirements for the case study axle.
4. A methodology using finite element modelling has been developed for evaluating the mechanical configuration of the sensor and optical fibre pattern. This methodology can be applied to a variety of axisymmetric axle geometries and has been verified against the test results of a laboratory prototype transducer.
5. The laboratory prototype optical weight sensor demonstrated good performance with accurate measurement of vertical load, and good immunity to non-vertical loads.
6. The system's sensitivity to environmental and temperature effects is understood, and can be eliminated with the use of more fully developed optical components.
7. The tests on the prototype sensor have confirmed the design principles of many components; namely: the sensor tube and fibre configurations; the selection and handling procedures of single-mode optical fibres; the selection of multi-mode pickup fibres; and the design of the electronic counter.
8. Discussions with various suppliers of fibre optic hardware indicate that many of the components for the weight sensor are now commercially available, and that because of current development work for military and civil aircraft applications, versions suitable for in-aircraft transducers should be available shortly.

RECOMMENDATIONS

The results from this project have demonstrated that a weight sensing transducer system with good measurement characteristics can be constructed using fibre optic technology. Before such a system can be used for an aircraft application, however, additional development remains to be done. As a result, the following recommendations for future work are made:

1. The investigation into the availability of optical components suitable for in-aircraft transducers must be pursued, particularly with regard to the splitter/coupler, fringe generator, and polarization-maintaining single-mode optical fibres. These investigations must address the packaging and miniaturization of the sensor-mounted components. Since the fringe generator is specific to the optical weight sensor, development will be required. The availability of appropriate laser diodes, (i.e. those with a stable frequency), also needs to be investigated.
2. The demonstration of the survivability aspects of optical components such as the fibre cables and connectors, needs to be performed. Such a demonstration can be achieved by installing these components on an actual aircraft and periodically monitoring performance over a large number of take-off and landing cycles. In addition, the survivability of bonded optical fibres under dynamic load and temperature conditions needs further examination.
3. A detailed design for the mechanical sensor and its mounting in an actual aircraft axle is needed. Construction, installation, and testing of the design must then be performed to determine its reliability under actual aircraft conditions.
4. Development of fibre winding and fibre trimming techniques is needed in order to ensure the required immunity to non-vertical loads and temperature changes. If smaller diameter single-mode optical fibres are to be used for miniaturization, the fibre handling procedures will need to be reviewed.
5. The influence of temperature gradients in aircraft axles on the performance of the sensor system needs to be examined. To achieve this, work is required in two areas. The first is to quantify actual temperature gradient profiles found in the aircraft axle environment, either through tests or through theoretical studies. The second is to modify the existing sensor system using proper optical components and to test it under known temperature gradient conditions.

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2. Fiber Optic Weight Sensor, TDC Report TP 2544, September 1979. DSL Dynamic Sciences Limited.
3. Development of a Fibre Optic Weight Sensor for an On-Board Aircraft Weight and Balance System, TDC Report TP 4367, February 1983. DSL Dynamic Sciences Limited.

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Développement

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Détecteur embarqué pour la pesée et le centrage des avions

Rapport sommaire

Préparé pour le
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ÉTUDE D'UN SYSTÈME EMBARQUÉ À FIBRES
OPTIQUES POUR LA PESÉE ET LE CENTRAGE DES AVIONS

RAPPORT RÉCAPITULATIF
RÉALISÉ POUR LE COMPTE DU
CENTRE DE DÉVELOPPEMENT DES TRANSPORTS,
TRANSPORTS CANADA

Also available in English



DSL DYNAMIC SCIENCES LIMITED
Montréal, Québec

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INTRODUCTION

Un système de pesée et de centrage d'avions est un système embarqué qui permet de calculer et d'afficher la masse et le centre de gravité d'un aéronef immobile au sol, indépendamment de tout autre système à l'extérieur de l'aéronef. On en connaît un certain nombre, mais aucun n'offre la fiabilité et la précision nécessaires pour en faire le principal système de calcul de la charge. Ils servent tout au plus à vérifier de façon approchée les calculs faits manuellement au sol sans compter que leur encombrement les rend inutilisables dans le domaine du transport léger.

Le fait que Canadair n'ait pas réussi à trouver un système de pesée et de centrage pouvant convenir à l'appareil CL-600 Challenger qu'elle est en train de construire a rallumé l'intérêt de Transports Canada pour un tel système. Deux marchés précédents adjugés à DSL Dynamic Sciences Limited avaient permis à celle-ci de montrer qu'une méthode interférométrique faisant appel à la technologie des fibres optiques pouvait être appliquée à la mesure des déformations dues aux charges s'exerçant sur les essieux d'un train d'atterrissage, ouvrant ainsi la voie à la conception d'un appareil détecteur utilisant cette technique. Les projets concernés sont décrits dans les ouvrages n° 1 et 2 de la bibliographie. Encouragée, DSL a soumis une proposition volontaire au Centre de développement des transports, Transports Canada, visant l'étude d'un détecteur à fibres optiques devant faire partie d'un système embarqué de pesée et de centrage d'avions. Le présent rapport constitue la version récapitulative du rapport complet qui a été publié par Transports Canada sous le numéro TP 4637 (réf. 3).

OBJECTIF DU PROGRAMME

Le programme d'ensemble vise l'étude et la construction d'un système de pesée et de centrage d'avions répondant aux besoins de l'aviation internationale.

OBJECTIF DU PROJET

Le projet visait la conception, l'étude et l'essai pratique d'un détecteur à fibres optiques devant faire partie d'un système embarqué de pesée et de centrage d'avions.

Pour cela, il fallait étudier un modèle de laboratoire conçu pour le train d'atterrissage d'un avion désigné et ensuite établir, dans des conditions de laboratoire contrôlées, que ce modèle pouvait effectivement mesurer les charges verticales s'exerçant sur ce même train.

APPROCHE ET TRAVAUX

L'approche préconisée a été de diviser le projet en deux phases, séparées par une phase d'examen critique du modèle.

Au cours de la première phase, un cahier des exigences générales et particulières concernant le détecteur a été élaboré. Le cahier des exigences générales (réf. 3), a défini les besoins auxquels devrait satisfaire le détecteur dans le cas d'un aéronef commercial quelconque, compte tenu des spécifications existantes ou proposées et des réactions connues des différents constructeurs et exploitants d'aéronefs. Ensuite, un cahier des exigences particulières a été fait, relatif aux détecteurs devant être montés sur le train avant et sur l'atterrisseur principal du Challenger.

L'étape suivante a été l'étude des différents composants mécaniques et optoélectroniques du détecteur, suivie d'une analyse de leur faisabilité. Les principaux travaux accomplis ont été les suivants:

- analyse des contraintes à l'aide de la méthode des éléments finis, dans le cas du train avant du Challenger équipé du détecteur.
- étude d'un modèle de laboratoire et de ses composants mécaniques et optoélectroniques.
- calcul approché des signaux de sortie obtenus dans toute la gamme des charges s'exerçant sur ce train.
- recherche analytique des erreurs possibles, de leur source et de leur influence sur la justesse et la fidélité des mesures.
- recherche sur l'existence des composants optiques nécessaires au système embarqué.
- préparatifs de l'examen critique du modèle.

Pour vérifier les concepts retenus et établir la faisabilité de chacun des composants du détecteur, un certain nombre d'expérimentations ont été nécessaires:

- vérification des résultats de l'étude des contraintes à l'aide de la méthode des éléments finis, en les comparant aux résultats des essais extensométriques réalisés sur un essieu cylindrique en charge, équipé d'un détecteur;
- recherche sur les manipulations des fibres optiques;
- fabrication et essai d'un circuit expérimental pour le comptage des franges d'interférence, en vue de son intégration au système étudié.

L'examen critique du modèle a eu lieu le 18 août 1982 à l'usine de la compagnie DSL. Etaient présents des représentants du CDT, du Conseil national de recherches, de Canadair, de de Havilland et d'Air Canada. A l'ordre du jour, l'avancement des travaux et l'approche préconisée pour la suite des travaux. L'un et l'autre furent approuvés, après qu'il fut constaté que le modèle proposé satisfaisait aux exigences générales et particulières définies. L'autorisation fut donnée de poursuivre les travaux comme prévu.

Les travaux de la deuxième phase ont débouché sur la réalisation et l'essai pratique d'un prototype de laboratoire du modèle approuvé. Pour cela, les composants mécaniques et optiques ont été achetés, montés et intégrés, en même temps que le compteur électronique, dans le prototype. En raison de leurs particularités, deux des composants optiques, le séparateur/coupleur et la génératrice de franges, n'ont pu être achetés, vu les sujétions de temps et d'argent imposées par le programme. Contraintes administratives, donc, plutôt que techniques. Des versions expérimentales de ces composants ont été fabriquées par DSL et intégrées dans le détecteur. De même, un banc d'essai dynamique et une chambre d'essais thermiques ont dû être étudiés et réalisés.

Les essais ont consisté à exercer des charges directement sur le détecteur, d'une part, et, d'autre part, sur le détecteur monté sur un support simulant un essieu. Dans le premier cas, il s'agissait de déterminer les caractéristiques du détecteur soumis à des charges verticales: sensibilité, linéarité, répétitivité des résultats et immunité aux charges non-verticales, le tout à l'abri de toute influence extérieure découlant de son montage sur un support. Dans le deuxième cas, il fallait vérifier le comportement théorique du détecteur monté. Enfin, les réponses du détecteur en fonction des variations de température ont également été déterminées dans le but de vérifier celles obtenues par calcul.

RESULTATS DES TRAVAUX

Les résultats des essais de charge statique et thermique auxquels a été soumis le modèle étudié sont récapitulés comme suit:

1. De façon générale, le système satisfait aux exigences définies, c'est-à-dire mesurer les charges verticales et être peu sensible aux charges non-verticales.
2. Excellentes aptitudes à mesurer les charges verticales; bonnes sensibilité, linéarité et répétitivité, sans aucune hystérésis.
3. Bonne corrélation du comptage de franges et des essais extensométriques avec les valeurs théoriques obtenues par la méthode des éléments finis.
4. Légère sensibilité aux charges non-verticales, attribuable aux procédés utilisés pour le bobinage et l'assemblage à chaud des fibres, défaut pouvant être corrigé par un affinement de ces procédés.

5. Aucune réaction induite constatée, une fois le transducteur monté sur l'essieu en simulation. Les écarts constatés sont attribuables à l'élasticité des connecteurs entre le détecteur et l'essieu.
6. Une certaine sensibilité aux variations de température et aux perturbations extérieures, telles que les bruits et les vibrations mécaniques. Elle est attribuable au fait que le séparateur/coupleur et le générateur de franges ont été fabriqués de toutes pièces sur place. Ce défaut peut être ramené à des niveaux acceptables par l'installation de composants optiques venus du commerce.
7. Une certaine sensibilité aux gradients thermiques le long du tube contenant le détecteur. Cette sensibilité des fibres n'a pu être déterminée avec précision à cause de la nature des essais et de la configuration du prototype.
8. L'effet contrasté des franges varie selon la charge et la température, en raison des variations dans l'état de polarisation de la lumière dans les deux fibres.
9. Après certaines modifications apportées au compteur électronique pour tenir compte des pertes attribuables au séparateur-coupleur expérimental, la justesse et la fidélité des mesures obtenues de ce compteur se sont accrues. Les erreurs dans le comptage électronique sont attribuables à l'effet de polarisation décrit ci-dessus.

CONCLUSIONS

Le modèle d'un appareil détecteur à fibres optiques devant faire partie d'un système embarqué pour la pesée et le centrage d'avions a été conçu et étudié, et un prototype de ce modèle a été construit et éprouvé dans des conditions de laboratoire contrôlées. Voici les conclusions pouvant être tirées de cette étude:

1. A partir des spécifications existantes ou proposées et après un sondage auprès des différents constructeurs et exploitants d'aéronefs, la circulaire ARP 1409 recommandée par la SAE en ce qui concerne les systèmes embarqués pour la pesée et le centrage d'avions a été considérée comme pouvant servir de document acceptable pour l'élaboration d'un cahier des exigences générales concernant l'étude d'un transducteur pour la pesée des avions.
2. Les exigences particulières de précision définies relativement aux transducteurs devant être montés sur le train avant et sur l'atterrisseur principal du Challenger ont montré qu'il était possible de définir un appareil pouvant satisfaire aux exigences de précision globales prescrites dans la circulaire ARP 1409, et qu'elles constituaient un grand progrès dans l'étude d'un tel détecteur.

3. Un modèle de détecteur a pu être conçu dont les composants mécaniques et optoélectroniques satisfont aux exigences de précision applicables à l'essieu de l'avion considéré.
4. Une technique d'analyse des contraintes faisant appel à la méthode des éléments finis a été élaborée, pour évaluer la configuration mécanique du détecteur ainsi que le positionnement de ses fibres optiques. Il a été trouvé que cette technique peut être appliquée à un grand nombre de géométries d'essieu offrant une symétrie axiale, et les résultats obtenus ont été validés par les essais sur le prototype de laboratoire.
5. Le prototype de laboratoire a donné satisfaction par des mesures précises des charges verticales et par une bonne immunité aux charges non-verticales.
6. La sensibilité du détecteur aux variations de température et aux perturbations extérieures a pu être élucidée; elle peut être corrigée par l'emploi de composants optiques bien au point.
7. Les essais du prototype ont vérifié la validité d'un bon nombre des concepts et options retenus: la configuration du détecteur et le positionnement de ses fibres optiques; la sélection et la manipulation des fibres monomodes; la sélection des fibres multimodes pour le captage des signaux et enfin le compteur électronique lui-même.
8. Nos contacts avec divers fournisseurs de matériels utilisant les fibres optiques nous ont révélé qu'un grand nombre de composants entrant dans la fabrication du détecteur sont d'ores et déjà sur le marché et que des modèles pouvant convenir à un système embarqué seraient bientôt sur le marché, vu les travaux de développement exigés pour l'aviation militaire et civile.

RECOMMANDATIONS

Cette étude a montré qu'il est possible de réaliser un appareil détecteur utilisant la technologie des fibres optiques. Cependant, des travaux de développement plus poussés sont encore nécessaires pour rendre un tel appareil utilisable à bord des avions. Nous recommandons donc que les travaux suivants soient exécutés:

1. Poursuivre l'exploration du marché des composants optiques à la recherche d'éléments convenant aux transducteurs pour systèmes embarqués, et notamment le séparateur/coupleur, le générateur de franges et les fibres optiques monomodes capables de conserver la polarisation. Cette recherche doit porter aussi sur le poids et l'encombrement des composants qui doivent être le plus légers et le plus compacts possible. Etant donné que le générateur de franges est particulier au détecteur à fibres optiques, des travaux d'adaptation seront nécessaires. Autre recherche: celle des diodes laser appropriés, c'est-à-dire ceux à régime continu.

2. Lancer une recherche sur la durée de vie estimée des composants optiques: câbles à fibres et connecteurs. Pour cela, on pourrait monter ces composants à bord d'un avion et constater périodiquement les résultats obtenus au bout d'un nombre assez grand de décollages et d'atterrissages. En outre, la durée de vie estimée des fibres optiques assemblées à chaud soumises à des charges et à des températures variables doit, elle aussi, être évaluée.
3. Faire l'étude détaillée de la partie mécanique du détecteur et de son montage sur l'essieu d'un train d'avion. Ce détecteur devra être alors construit, monté et essayé dans des conditions réelles de service pour en déterminer la fiabilité.
4. Les procédés de bobinage et de sectionnement des fibres optiques devront être étudiés de près afin de donner à celles-ci l'immunité voulue aux charges non-verticales et aux variations de température. Si des fibres monomodes de diamètre encore plus fin étaient exigées par la miniaturisation des composants, les procédés devront être réexaminés.
5. Il faudra examiner de près l'influence des gradients de température dans les essieux sur le rendement de l'appareil détecteur. Pour cela, la recherche devra se faire sur deux fronts. D'abord, dresser le profil réel des températures dans l'entourage immédiat des essieux, soit par des mesures, soit par le calcul. Ensuite, adapter le système par l'emploi des composants optiques adéquats et en faire l'essai dans des conditions contrôlées, c'est-à-dire à gradients de température imposés.

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**DEVELOPMENT OF A FIBRE OPTIC
WEIGHT SENSOR FOR AN ON-BOARD AIRCRAFT
WEIGHT AND BALANCE SYSTEM**

FINAL REPORT

Prepared for
Transportation Development Centre
Transport Canada

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DTC 301
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SL Dynamic Sciences Limited



The contents of this report reflect the views of the contractor and not necessarily the official views or policies of the Transportation Development Centre, Transport Canada.

DEVELOPMENT OF A FIBRE OPTIC
WEIGHT SENSOR FOR AN ON-BOARD AIRCRAFT
WEIGHT AND BALANCE SYSTEM

FINAL REPORT
prepared for
TRANSPORTATION DEVELOPMENT CENTRE
TRANSPORT CANADA



DSL DYNAMIC SCIENCES LIMITED
Montreal, Quebec

Report C162-04
February, 1983

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17. Résumé Le rapport décrit un appareil détecteur à fibres optiques devant faire partie d'un système de pesée et de centrage d'avions, ainsi que les expérimentations dont il a fait l'objet. Cet appareil a été étudié pour satisfaire aux exigences générales définies ainsi qu'aux exigences particulières de l'avion CL-600 Challenger de Canadair. Un prototype a été construit et soumis à des essais en laboratoire pour déterminer le comportement sous des conditions de charge et de température contrôlées. Il a montré une excellente précision dans la mesure des charges verticales et une grande insensibilité aux charges non-verticales. Les expérimentations faites sur deux composants de l'appareil ont montré une certaine sensibilité aux changements de température et de milieu, défaut qui pourra être corrigé par une étude plus poussée de ces composants.					
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SUMMARY

An on-board aircraft weight and balance system (AWABS) provides a measurement and display of aircraft weight and centre of gravity under static ground conditions. The market for such a system is good, but, to date, no commercial system has achieved the reliability and accuracy required for use as a primary load control system.

Because of this market potential, DSL Dynamic Sciences Limited, under the joint sponsorship of the Transportation Development Centre of Transport Canada and the National Research Council, undertook a project whose objectives were to design, develop, and demonstrate a fibre optic weight sensor suitable for use as an element in an on-board AWABS. Bridge funding was provided by the Unsolicited Proposals program of the Department of Supply and Services Science Centre.

The project was divided into two phases, with an intervening design review. In the first phase, general requirements for the sensor which are applicable to any aircraft were defined, as well as specific requirements for the case study of the Canadair CL-600 Challenger. Analytical and experimental activities were undertaken to establish the viability of the mechanical, optical, and electronic design concepts for the sensor system. This work culminated in a design for the system, an estimate of its output under expected axle loadings, and an estimate of its behaviour in a combined worst case error situation. The design and analyses were presented at the design review, after which approval was given to proceed with the second phase of the project.

The second phase consisted of the development and demonstration of a laboratory prototype of the approved design. Optical, electronic, and mechanical components for the sensor and test apparatus were designed, procured or fabricated, and integrated. Because of procurement difficulties, experimental versions of two optical components were used. The system was then extensively tested to determine its performance under load and temperature variations in the laboratory.

It was concluded from the test results that the objectives of the project had been achieved; namely, that a sensor system utilizing fibre optic technology has been designed and demonstrated which provides a sensitive measure of vertical load, with high immunity to non-vertical loads. It was also concluded that the sensitivity of the prototype system to temperature and environmental disturbances was due to two of the experimental optical components, and that this sensitivity can be either eliminated or reduced to acceptable levels.

While the project has demonstrated that the fibre optic weight sensor can meet the measurement requirements for an

on-board AWABS, additional development remains to be done before the sensor can be used for an aircraft application. Recommendations for future work include the continued investigation of availability of optical components for in-aircraft sensors; evaluation of their survivability aspects; development of the sensor mount; and quantification of the effect of temperature gradients on the sensor. The culmination of this future work will be marked by the testing of a practical weight sensor unit mounted in an actual aircraft.

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1. INTRODUCTION

This is the final report on a project undertaken by DSL Dynamic Sciences Limited (DSL), to develop a fibre optic weight sensor as part of an aircraft on-board weight and balance system.

The project was conducted under the joint sponsorship of the Transportation Development Centre of Transport Canada and the National Research Council, with bridge funding provided by the Unsolicited Proposals program of the Department of Supply and Services Science Centre.

1.1 Background

An Aircraft Weight and Balance System (AWABS) provides on-board measurement and display of aircraft weight and centre of gravity under ground static conditions, independently of any system external to the aircraft.

Such systems exist, but none have achieved the reliability and accuracy required for them to be employed as the primary load control system. Where used, they provide only an approximate check on the manual calculations performed on the ground. In addition, they cannot be fitted to small transport aircraft such as the Canadair Challenger.

Initial interest was kindled by Canadair's failure to identify an acceptable AWABS for the Challenger. An analysis of the reasons for this failure resulted in a concept of an AWABS using optical transducers to detect deflections inside the landing gear axles. Such transducers would be electrically passive, highly sensitive to deflections, and lightweight.

The optical technique chosen was the 'fibre optic strain gauge', which operates on the principle that light takes a longer or shorter time to pass through a glass fibre which is stretched or compressed. An interferometer incorporating this technique was constructed, and the feasibility of the concept was established. Reference 1 is a report on this work.

A preliminary design for an aircraft weight sensor was produced and presented to the Canadian aircraft manufacturers, who concluded that it was practicable. Reference 2 is a report on this work.

DSL was invited to present a paper on this work to the Society of Allied Weight Engineers (SAWE) 39th Annual Conference in May, 1980. This paper was also published in

the SAWE Journal, where it won the award for best original technical article; a reprint of the article is provided in Appendix A. The worldwide response to this article encouraged DSL to submit an Unsolicited Proposal for the first stage in the development of such a weight sensor.

This report documents the development work carried out under the ensuing contract.

1.2 Program Objective

The overall objective of the AWABS program is the development and production of on-board aircraft weight and balance systems to meet worldwide requirements.

There is no question that a worldwide market for an accurate and reliable AWABS exists. Such a system offers significant improvements in aircraft operational safety, and appreciable reductions in operating costs.

1.3 Project Objective and Scope

The objective of this project was to design, develop, and demonstrate a fibre optic weight sensor suitable for use as an element in an aircraft on-board weight and balance system.

It is important to note that the scope includes the sensor only. Consideration of the AWABS system as a whole, or any components of the system other than the weight sensors, was specifically excluded.

The objective was to be achieved by the development of a laboratory model of a weight sensor for a specific aircraft landing gear and demonstrating, under controlled laboratory conditions, that it could measure the vertical loads produced in the candidate landing gear.

Development of the laboratory model was to be preceded by

- a definition of the requirements to be met by an aircraft on-board weight sensor, both general (i.e. for any aircraft) and for a specific candidate aircraft.
- in depth examination of design concepts to establish their viability, including a stress analysis of the candidate axle and sensor combination.
- estimation of sensor outputs and identification of the source and significance of possible error-generating inputs.

- confirmation that the proposed design would meet both the general and specific requirements.

The laboratory model was then to be developed and subjected to static tests to ascertain its sensitivity to vertical loads, and insensitivity to non-vertical loads and to temperature variations.

2. PROJECT OVERVIEW

The project was essentially performed in two phases, separated by a design review conducted by representatives of government and industry. The main activities performed are summarized below.

The first activity was the establishment of the 'general' and the 'specific' requirements for the AWABS transducer. The general requirements were those that apply to all aircraft. For the specific requirements, the Canadair Challenger nose gear was chosen as a case study. Further details are provided in Section 3 of this report.

The design stage was then entered into, aimed at establishing the viability of design concepts. Significant activities included:

- a stress analysis of the Challenger nose gear axle with sensor fitted.
- an estimation of sensor outputs over the full load range.
- an identification and quantification of sources of error.
- an error analysis, relating error sources to the error 'budget'.
- preparation for a design review.

These activities are discussed in detail in Section 3 of this report.

A design review was held at DSL's plant on 18 August, 1982, attended by representatives of TDC, NRC, Canadair, de Havilland, and Air Canada. Achievements to date and the proposed approach for the balance of the project were reviewed and endorsed. It was agreed that the proposed design met the general and specific requirements, and a go-ahead was given for completion of the project as planned.

Components were acquired or fabricated, and a laboratory prototype sensor was constructed. Difficulties were experienced in the procurement of certain specific fibre optic components which necessitated deviation from the planned objectives.

In addition to the sensor itself, a test jig for applying known loads to the sensor and a jig for winding fibre onto

the sensor tube were designed and built. Details of these activities are found in Section 4 of this report.

The laboratory prototype was subjected to a series of tests to establish its sensitivity to wheel loads (vertical) and insensitivity to non-vertical loads caused, for example, by ramps, brakes, chocks, and wind, within the established error budget. Response to temperature variations was also investigated and theoretical predictions confirmed. Tests were performed both with loads applied directly to the sensor tube, and with loads applied to a simulated axle into which the sensor was installed. The tests, and the results obtained, are discussed in Section 5 of this report.

3. ANALYSIS AND DESIGN

The analysis and design activities which led to the design review commenced with a definition of the requirements which the sensor would have to meet, and ranged through a number of investigations into the optical, electronic, and mechanical components of the system culminating in an error analysis of the complete sensor. This section details the results of these activities.

3.1 Requirements Definition

Existing and proposed standards for AWABS were reviewed, including the Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 1409 (3)*. A survey of aircraft manufacturers and operators was performed to elicit their comments on the ARP and to determine requirements for specific aircraft. A list of general requirements (i.e. applicable to any type of aircraft) for the weight sensor was produced; this document is provided as Appendix B; ARP 1409 was found to be generally acceptable.

The Canadair CL-600 'Challenger' was then chosen for specific case study and, with the cooperation of Canadair personnel, specific requirements for weight sensors for the Challenger were produced - the resulting document is provided as Appendix C. These requirements formed the basis of subsequent design activities.

Significant results from the requirements definition are summarized in Figures 1 and 2 which show the allowable error on the measurement of load at each wheel of the Challenger in order to meet the accuracy requirements for determination of aircraft weight and centre of gravity position.

3.2 Transducer Design

The transducer design activity fell into two major categories:

- mechanical design, which concerned the sensor tube and the optical paths on the tube.
- opto-electronic design which concerned the optical and electronic components and the handling techniques for single-mode fibre.

* Numbers in brackets refer to the references listed on page 39.

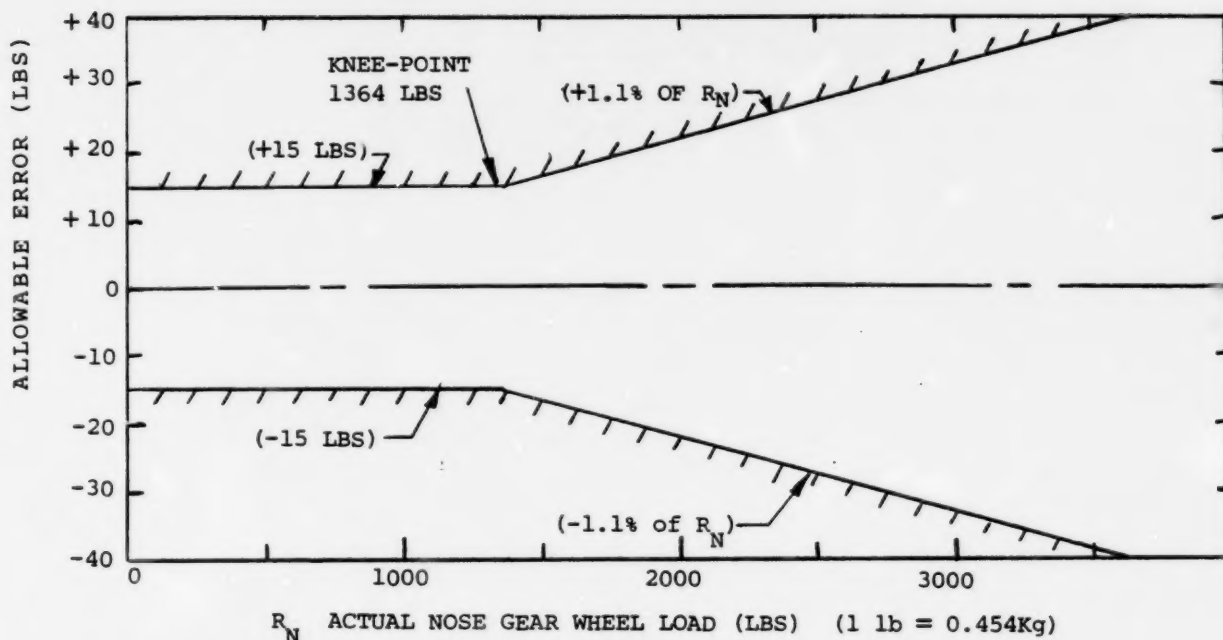


FIGURE 1 ALLOWABLE TRANSDUCER ERROR VERSUS WHEEL LOAD
- CHALLENGER NOSE GEAR

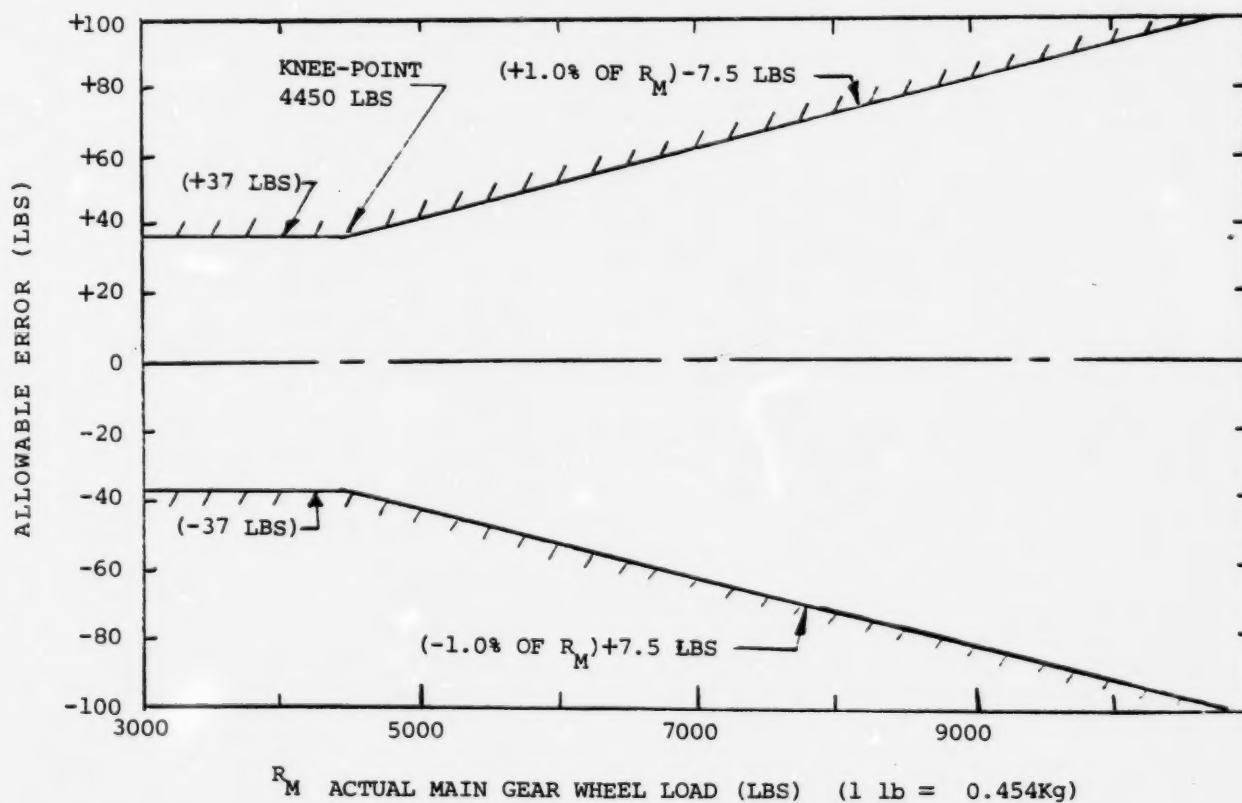


FIGURE 2 ALLOWABLE TRANSDUCER ERROR VERSUS WHEEL LOAD
- CHALLENGER MAIN GEAR

3.2.1 Mechanical Design

The preceding project had established the conceptual design of a flexible sensor tube which would have optical fibres bonded to it, and would be attached at its ends to the inside of the landing gear axle.

To determine the optimal configuration of the sensor tube, analyses were made, using finite element techniques, of the sensor installed in the case study axle of the Challenger nose landing gear. The result of this work was the definition of an optimal length for the slightly tapered sensor and its position within the axle such that the sensor would have the required sensitivity to the vertical loads, and immunity to non-vertical loads and localized stress fields. The finite element model of the selected sensor is shown in Figure 3.

Further finite element analyses were performed to determine the optimal path configuration of the bonded optical fibres. The path, shown in Figure 4, consists of the two fibres wound around the sensor along forty-five degree diagonals to the tube axis which cross each other at the middle of the tube. This configuration essentially measures the shear strain in the tube due to vertical loads, and is insensitive to strains due to lateral loads or bending moments. In addition to providing specific results for the case study axle and sensor, the finite element modelling resulted in a general methodology which can be applied to the optimal design of sensors for a variety of axisymmetric axle geometries including both cylindrical and tapered designs.

A study was made of mechanisms for mounting the sensor tube within the axle. Mechanisms used in existing AWABS were examined and a variety of mounting concepts were devised which provide a means of rigidly connecting the sensor ends to the axle so that deflections of the axle under load are transmitted to the sensor tube. Sufficient analysis was undertaken to satisfy questions of feasibility. Final choice of a concept and detailed design were not undertaken.

To verify the theoretical analyses, an experimental sensor tube was designed and constructed. It was instrumented with conventional electrical strain gauges, and installed in a simplified axle having a constant cylindrical diameter. The axle/sensor assembly was installed in a test rig and a series of static loads in various directions was applied to the axle and the output from the strain gauges were recorded. The results of the tests verified the predicted behaviour that shear strain devices positioned in the middle of the sensor tube would provide an output which is both linearly proportional

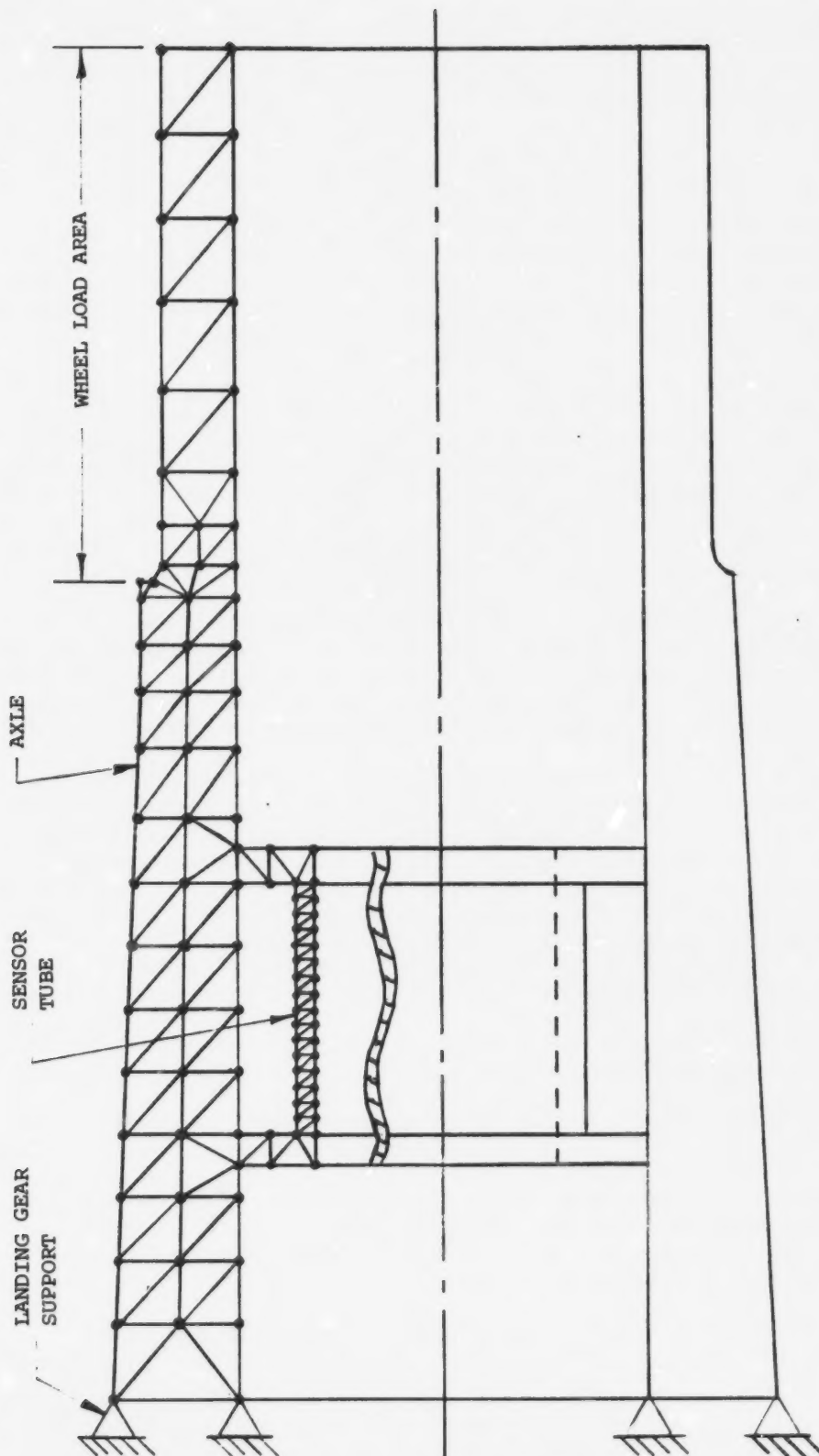


FIGURE 3 FINITE ELEMENT MODEL OF
CASE STUDY AXLE AND
TRANSDUCER

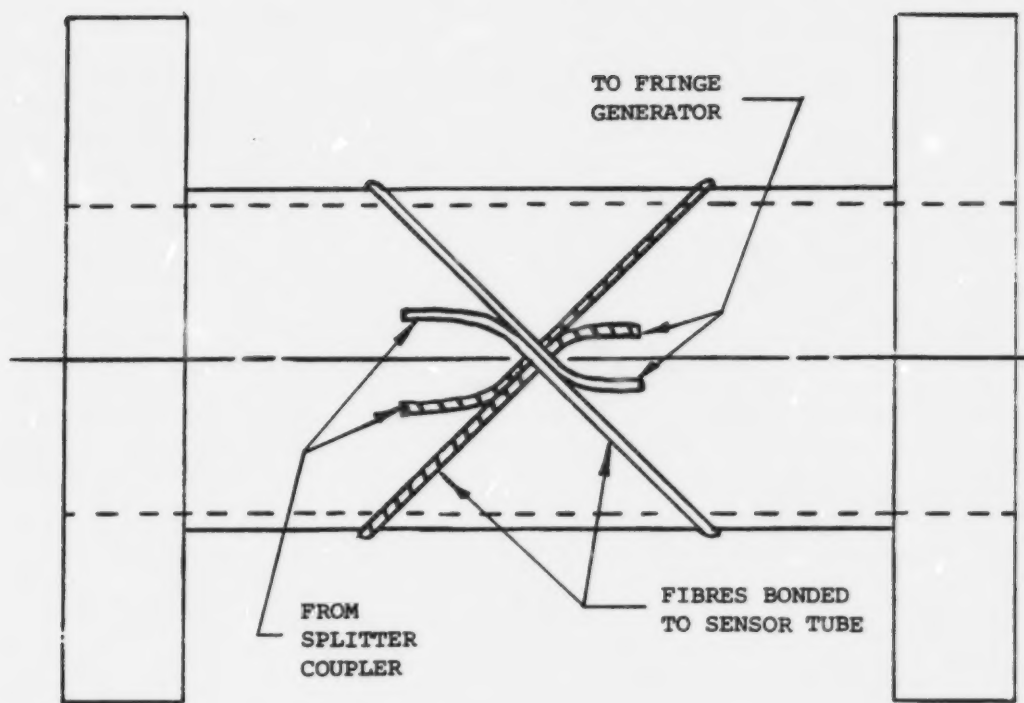


FIGURE 4 ARRANGEMENT OF FIBRES ON SENSOR TUBE
(ONE TURN OF FIBRES SHOWN)

to vertical loads, and insensitive to non-vertical loads and associated bending moments. The tests also confirmed that the strains on the sensor were low enough to ensure that bonded optical fibres would have a satisfactory fatigue life in an aircraft axle.

3.2.2 Optical Design

In the preceding project, a number of generic optical components had been identified which could be integrated to produce the fibre optic weight sensor shown in Appendix A. Those components comprised a laser, single-mode fibre and connectors, splitter/coupler, fringe generator, coherent fibre bundle and connectors, and photo-diodes. Following a review of this system in terms of its light losses and the most recent advances in fibre optic technology, it was decided to replace the coherent fibre bundle and connectors with a simpler arrangement of discrete multi-mode fibres and connectors having a lower light loss and a much lower cost.

Requirements and specifications for each optical component for the prototype transducer system were then established, and procurement sources were sought. Single and multi-mode fibres, multi-mode connectors, and photo-diodes were found to be commercially available, and samples were obtained for evaluation in the laboratory prior to final selection of these components. Various suitable lasers were available and one was selected and procured for use in the laboratory.

The splitter/coupler, fringe generator, and single-mode fibre connectors were not available as off-the-shelf components. Quotations for these devices were solicited from a number of optical component manufacturers, enabling the selection of suppliers for the splitter/coupler and connectors. However, a suitable supplier was not located who was interested in producing a "one only" prototype fringe generator. As a result, it was decided to use an experimental fringe generator for the laboratory sensor system, as described in Chapter 4.

The complete design of the prototype optical system is shown in Figure 5, with each component defined below:

Laser: A 5mW, visible red, helium-neon laser (Ealing Scientific, part no. 25-0860).

Laser-to-fibre coupling: A microscope objective lens, mounted on a lens holder, focusses the laser beam onto the end of the single-mode fibre which is clamped in a fibre-holder mounted on an X-Y positioning device.

Single-mode fibre: ITT type T-1601. This is an upgraded version of the T-110 fibre used in the original feasibility study (1).

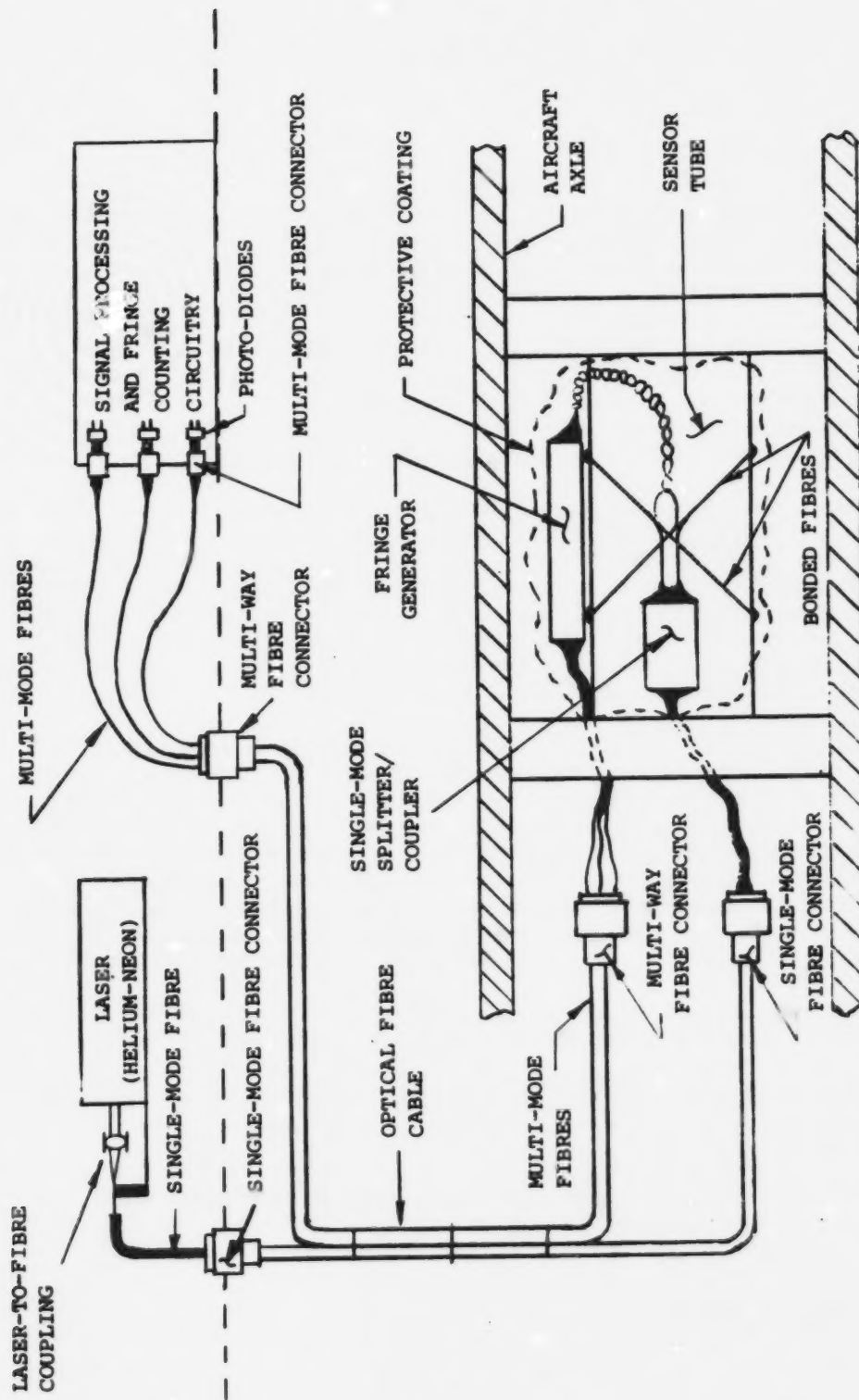


FIGURE 5 TRANSDUCER SYSTEM SCHEMATIC

Single-mode fibre connectors: TRW connectors designed specifically for the T-1601 fibre.

Splitter/coupler: This is a passive 3-port single-mode fibre device which divides the light from the input port into two beams of equal intensity. The device is mounted next to the bonded portions of the fibres on the sensor tube.

Sensor tube: The sensor tube consists of a thin-wall steel tube with provision for rigid attachment to the inside of the axle. Two lengths of stripped T-1601 fibre are wound onto the tube, as shown in Figure 4, and bonded in place using a cyanoacrylate strain gauge adhesive. Sufficient lengths of protected fibre are provided at the input and output ends of each winding to allow for connection to the splitter/coupler and to the fringe generator.

Fringe generator: In this device, the light from the two output fibres is made to interfere. The resulting interference pattern is focussed onto the ends of three multi-mode "pick-up" fibres. To minimize unbonded lengths of single-mode fibre, the device is mounted on the sensor tube, close to the fibre cross-point.

Pick-up fibres: Three Corning, SDF type, multi-mode step-index fibres, or similar, pick up information about the position of the fringes in the fringe generator and carry it to three photo-electric sensors at the input of the fringe-counting circuit.

Multi-mode fibre connectors: Connectors such as Amphenol type 801-102-5004 or ITT type OCN-04 may be used for installation and to isolate various components of the sensor system for maintenance purposes.

Photo-sensors: These are Motorola PIN photo-diodes type MFOD102F, designed specifically for use in fibre optic applications. They are mounted in AMP active device bushings for interfacing with the pick-up fibres.

The construction of the fibre optic sensor also required investigation and development of single-mode fibre handling techniques such as the removal of protective coatings, cleaving of fibre ends, winding and bonding of stripped fibres, and splicing. Currently available techniques were identified and evaluated in the laboratory; this work resulted in the establishment of preferred fibre handling procedures.

3.2.3 Electronic Design

The only electronic component of the weight sensor system is the fringe counter. Firstly, the nature of the fringe pattern was analyzed in order to determine the requirements for

the counter, in particular, counter range, resolution, accuracy, and dynamic response. Other design objectives including insensitivity to changes in fringe intensity and in contrast were also established. A survey of existing fringe counters was undertaken, and none that were appropriate to the weight sensor application were found to be commercially available; it was therefore decided to design a special purpose device.

The design of the fringe counter involved a survey of counting techniques and a definition of the optimal pick-up geometry shown in Figure 6. Using sensors selected in collaboration with the optical design activity, signal processing and fringe counting circuits were designed. The signal processing circuit converts the three input signals from the photo-diodes into two sine and cosine signals having no d.c. offset. These are fed to an integer count circuit where they are shaped and counted, the direction of the count (up or down) depending on the relative phase angle of the two. This count is accumulated and displayed on the three most significant digits of a 5-digit, 7-segment, LED type display. The two signals from the signal processing circuit are also fed to a fractional count circuit whose output provides the two least significant digits of the display.

A breadboard version of the counter was built and tested at room temperature, using both optical and ideal electrical input signals. The counter showed excellent performance with the following characteristics:

Total count capability	1000	fringes
Resolution	0.01	fringes
Accuracy	± .01	fringes
Minimum optical input level	< 0.5 μ W	peak-to-peak
Maximum input frequency	> 25	kHz

3.2.4 Component Availability for In-aircraft Transducers

This project was concerned primarily with the development and testing of a laboratory prototype optical weight sensor. However, it was appropriate at this stage to investigate the availability of the various optical components that would be required for an in-aircraft sensor. These include:

- coherent light source (laser)
- single and multi-mode fibres and cables
- single and multi-mode fibre connectors
- single-mode fibre splitter/coupler
- fringe generator.

Laser: Light weight, compact versions of the helium-neon laser used in the laboratory prototype are now readily available.

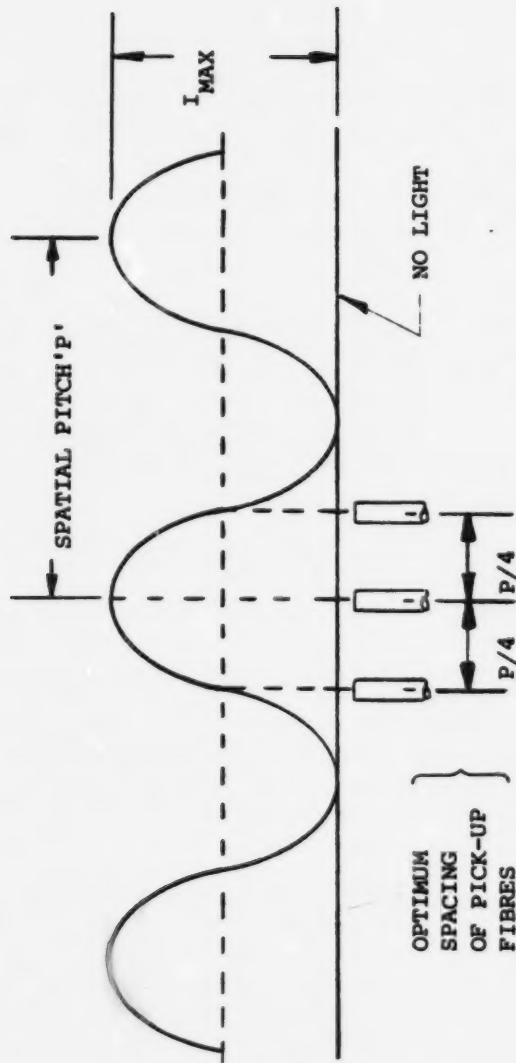


FIGURE 6 NATURE OF FRINGE PATTERN:
INTENSITY OF LIGHT VERSUS DISTANCE

An alternative to the gas laser is the smaller, more rugged, semiconductor laser diode. Single-mode versions of these lasers with integral single-mode fibre 'pigtails' are now commercially available. However, these lasers exhibit abrupt changes in wavelength under certain operating conditions, which renders them inappropriate to strain-sensing applications. Solutions to this problem have been identified (4) , and it is expected that military approved devices will be available in the near future.

Fibres and cables: Single-mode fibres with polarization maintaining properties are now produced by a number of Canadian and U.S. manufacturers, and ITT has recently introduced a polarization-maintaining version of the T-1601 fibre used in this project. Multi-mode fibres are used extensively by the communications industry, and consequently are highly developed and widely available.

Contact with cable manufacturers such as Belden, ITT and Pirelli Cable indicate that the development of fibre optic cable suitable for use in very severe environments is well underway. Military standards for fibre optic cables are presently being prepared and a number of experimental fibre optic systems are being evaluated by both military and civilian aircraft manufacturers (5) .

Fibre optic connectors: Military approved multi-mode fibre connectors are produced by most of the major connector manufacturers and have been in use for several years. Therefore availability is no problem.

Single-mode fibre connectors are under development by TRW, Deutsch and others. The TRW single-mode connector for the T-1601 fibre is being used by the U.S. Naval Research Laboratory, and conforms with the vibration requirements of Mil. Std 202E (6) . Samples of this connector were acquired and tried out during the project.

Single-mode splitter/couplers: For this project, a fibre optic component manufacturer was contracted to develop and build a prototype splitter/coupler using ITT's T-1601 fibre. The manufacturer found that presently available splitting techniques could not be applied to this fibre because of its particular refractive index geometry. However, ITT have recently developed a new version of the T-1601 fibre which can be split using available techniques. 70mm long x 7mm diameter splitter/couplers made from this fibre have been developed and are now commercially available; a much smaller, mil. spec. version is being developed for U.S. Naval Research Laboratories.

Because of their applicability to both fibre optic interferometry and long distance telecommunications, it is likely that these devices will be developed very rapidly and will soon be widely available.

Fringe generator: The fringe generator is specific to the fibre optic strain gauge, and is not commercially available at present. Investigations and experimentation by DSL have demonstrated the feasibility of the device and that the optics involved can be quite simple. Work is required to investigate the packaging and survivability aspects of the fringe generator for in-aircraft use. Early contacts with companies experienced in the design and manufacturing of optical components showed that there was interest in producing such a device, but not within the time and cost constraints for this project. Further contacts with these companies or others are needed to provide a meaningful assessment of future availability.

3.3 Error Analysis

Having established the accuracy requirements for the case study and a design for the transducer, it was necessary to bring the two together and to establish whether or not the total transducer system could indeed provide the required accuracy. A detailed error analysis was undertaken to meet this need.

The objectives of the error analysis were to identify possible sources of error, mechanical, optical, and electronic, to evaluate the significance of all identifiable errors, to estimate total error under combined worst case conditions, and to relate this total to the established requirements.

Figure 7 shows the accuracy requirement (as in Figure 1 above) and the worst case error estimates. The total worst case estimate never exceeds 45% of the requirement.

Mechanical errors include those due to installation and manufacturing tolerances. The tolerances assumed for installation are consistent with normal practice in the aircraft industry. Mechanical errors are shown in the top two sections of the curve. The significant sources of error are rotation of the sensor, axial misalignment of the fibres on the sensor, and, for tapered axles only, axial misalignment of the transducer in the axle.

The third (lowest) section includes optical errors at the sensor as well as errors from signal processing; that is, all opto-electronic errors in the final digital fringe count output. (For use of electrical gauges on the transducer, this would be replaced by errors due to gauge self-heating, temperature, aging, amplification, filtering and analog-to-digital conversion).

Although it is most encouraging to note that the optical and signal processing contributes so little to the total error,

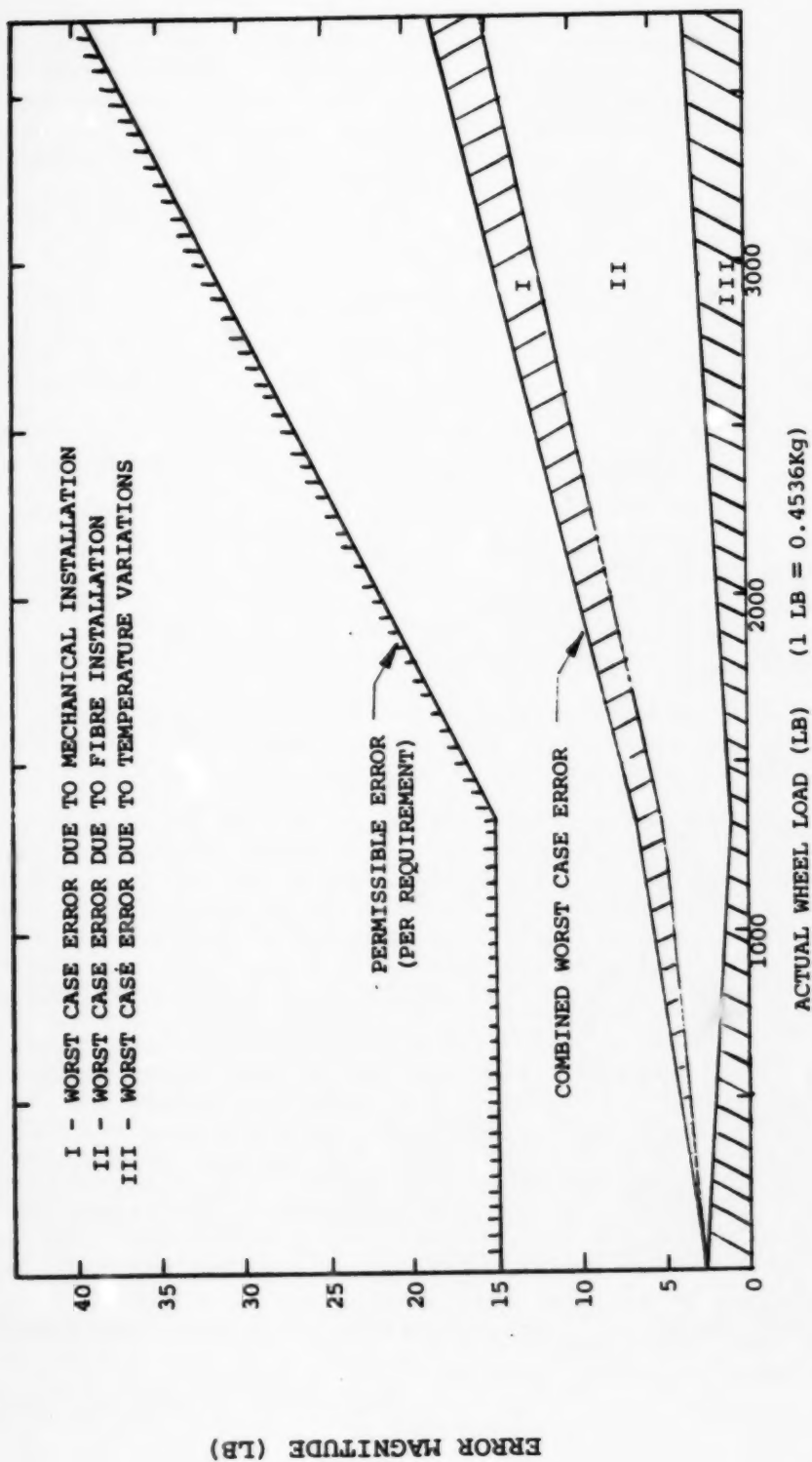


FIGURE 7 ERROR ESTIMATES OF TRANSDUCER FOR CASE STUDY AXLE

one potential source of error is excluded from this analysis. The effect of temperature gradient nonlinearities cannot be estimated without further knowledge of the dynamic temperature environment in the axle. This, however, should not pose a problem for axles without brakes, such as the case study. If it becomes a problem (in other axles), a variety of means are available to eliminate or reduce temperature gradient effects.

The error analysis shows that the proposed design easily meets the established accuracy requirements, and that optoelectronic errors form only a small proportion of the total error.

4. LABORATORY PROTOTYPE TRANSDUCER

Following the design review, permission was obtained to complete the project as planned. The procurement and fabrication of components, and the integration of a laboratory prototype transducer were carried out; these activities are discussed in this chapter. Due to the specialized nature of some of the optical components, deviations from the transducer design presented in chapter 3 were made; these are also discussed.

4.1 Procured Components

A mechanical sensor tube to be used in the testing was designed at DSL, and is shown in Figure 8. The sensor consists of a $3\frac{1}{2}$ inch long, 1 inch diameter thin-wall steel tube * and steel end plates which are bolted to the load test rig described in the next chapter. A winding jig used in positioning the optical fibres on the sensor tube was also designed, and is shown in Figure 9. The mechanical sensor, winding jig, and load test rig were then procured from a precision machine shop. The multi-mode fibre and connectors for both single and multi-mode fibre were also obtained. (The laser and single-mode fibre had already been procured during the design and analysis phase of the project).

A serious difficulty occurred in the procurement of the splitter/coupler due to the inability of the selected supplier to fabricate the device using ITT T-1601 single-mode fibre. Numerous possible solutions to this problem were investigated, including the use of different types of fibre and alternative splitter/coupler suppliers, but no satisfactory solution was found. Therefore, it was decided to dispense with the splitter/coupler for the laboratory prototype and to implement its function using a beam-splitting cube, mirror, and two microscope objective lenses. (It was later learned that ITT had just produced a modified T-1601 fibre and were in the process of developing compatible splitter/couplers, as discussed in section 3.2.4).

- * For this project, the sensor tube was slightly larger than would be used for a production transducer for the Challenger nose gear axle. This was done to facilitate procurement and fabrication of the sensor. Miniaturization of the sensor tube and optical components was not considered cost-effective at this stage.

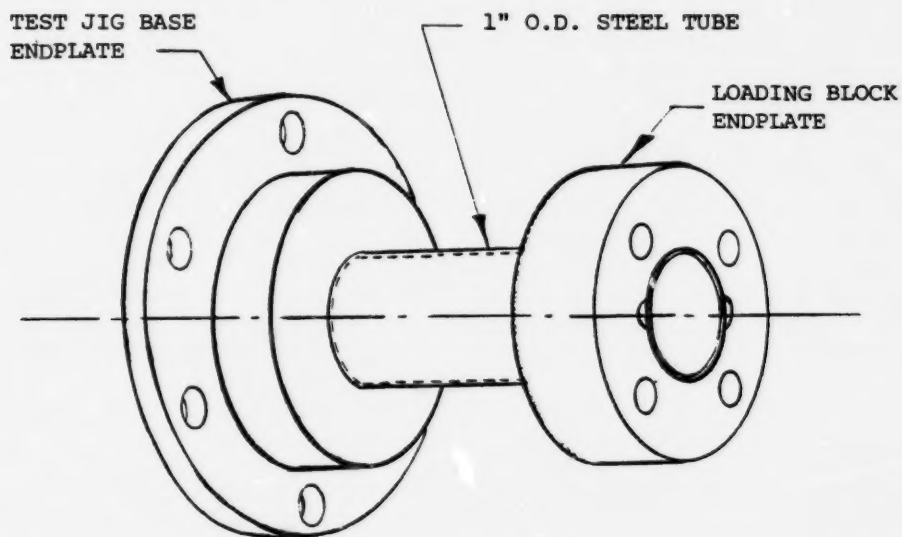


FIGURE 8 TEST SENSOR TUBE

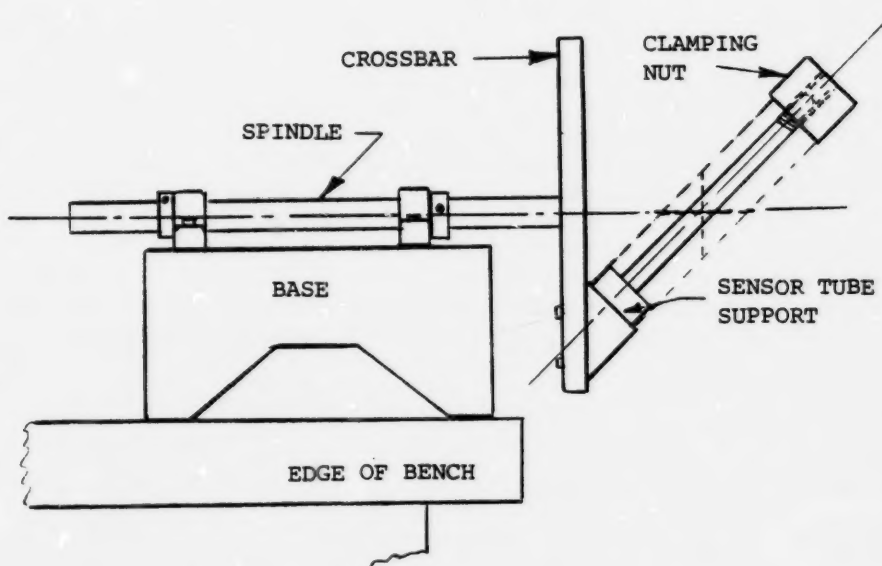


FIGURE 9 WINDING JIG

The lack of a proper splitter/coupler had significant impact on the performance of the prototype transducer system due to larger light losses and to the necessary lengths of unbonded fibres at the input to the sensor tube.

4.2 Fabricated Components

Work was carried out at DSL to complete the construction of the sensor tube; namely: the winding and bonding of the strain-sensing optical fibres, and bonding of the end plates to the sensor tube. The winding jig was used to position the fibres along two diagonal paths at 45 degrees to the axis of the sensor. Four complete turns for each fibre were made.

As discussed in the previous chapter, a prototype model of the fringe generator was not available. Consequently, a laboratory experimental model, shown in Figure 10, was constructed at DSL. The fringe generator consists of the output ends of the sensor fibres, three multi-mode pickup fibres, and a cylindrical focussing lens, all of which are fixed to glass plates.

4.3 Integration

The optical, mechanical, and electronic components were integrated to produce the laboratory prototype transducer system shown in Figure 11. As described earlier, the most significant deviation from the designed configuration was the implementation of the splitter/coupler function using a beam-splitting cube, mirror, and focussing lenses. The single-mode fibre connectors, which had been acquired and evaluated, were omitted in order to compensate as much as possible for the large light losses associated with the splitter/coupler replacement. It was initially intended to have very short output lengths of fibre by mounting the fringe generator inside the sensor tube. However, because small initial adjustments were required, the fringe generator had to be mounted a short distance away from the sensor.

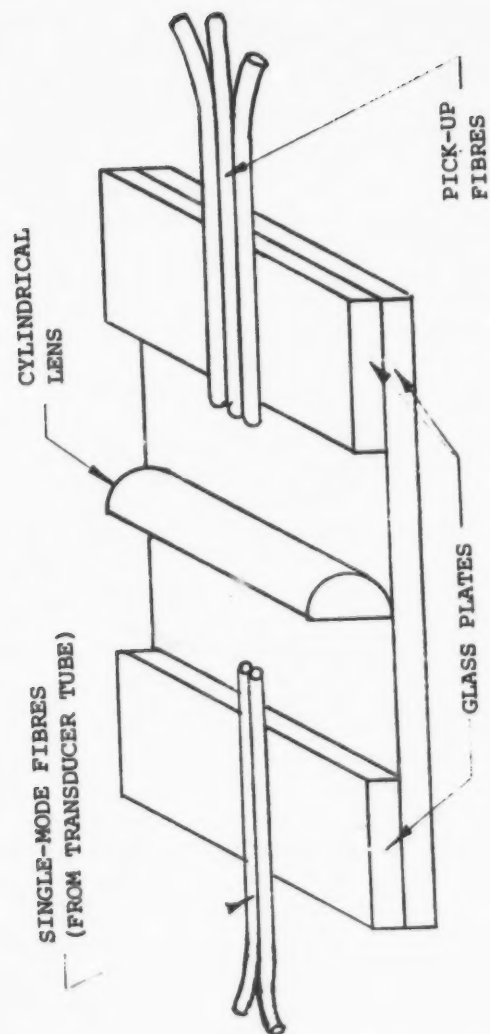


FIGURE 10 EXPERIMENTAL FRINGE GENERATOR

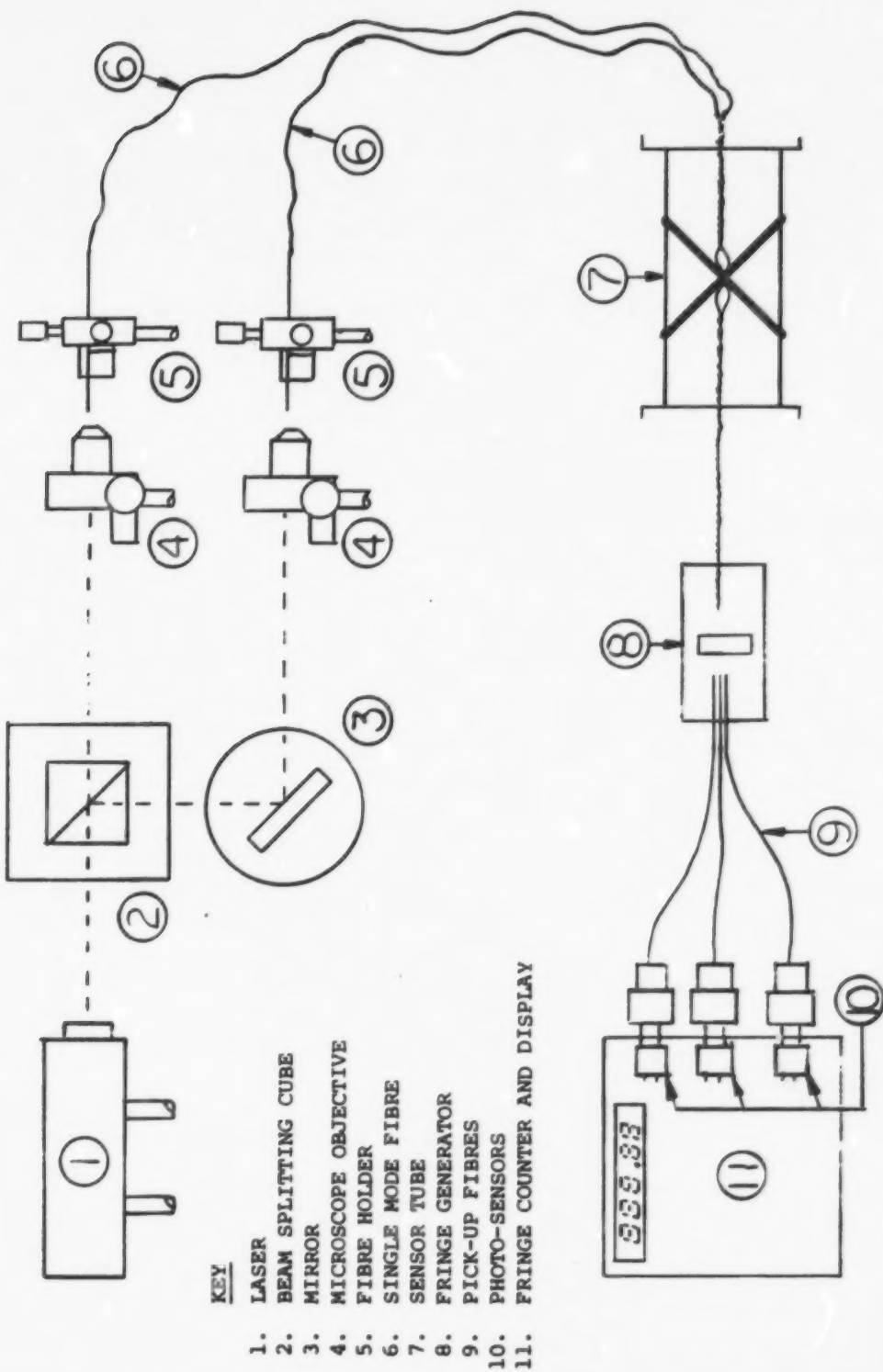


FIGURE 11 LABORATORY PROTOTYPE TRANSDUCER SYSTEM

5. TESTING

This chapter describes the testing of the laboratory prototype transducer system. The objectives of the tests are presented, followed by descriptions of the apparatus on which the system was tested, and test procedures. The results are then discussed, along with various observations concerning the performance of the transducer system.

5.1 Objectives

The primary objective was to test the prototype transducer system under controlled laboratory conditions to determine its compliance with design requirements for load and temperature as given in Appendix B. In particular, the objective was to demonstrate that the transducer is capable of measuring static vertical weight to the required accuracy in the presence of non-vertical loads and temperature variations.

Additional objectives were to evaluate the operation of the electronic fringe counter and prototype optical components, and to verify the behaviour of the transducer which had, at that point, only been studied analytically.

5.2 Test Approach

It was decided to test the transducer system in two configurations: firstly the sensor alone, and secondly, in combination with a simulated axle. The former offered several advantages including: a small, low cost, handleable test rig; more accuracy in application and measurement of loads; and the capability of applying simultaneous loads. In addition, testing of the sensor alone permitted quantification of the system characteristics without any external influences due to the axle or the sensor mounts. The loads which were applied to the sensor alone corresponded to stress levels equivalent to those of the sensor mounted in the case study axle over the full load range.

Tests were also performed on the sensor mounted in a simulated axle assembly. The purpose of these tests was to verify the sensor characteristics as determined by the finite element model and to ensure that mounting it in an axle would not introduce any unexpected behaviour. As a result, the range of stress levels corresponding to in-aircraft installation was not required. Actual stress levels were about a third to half the maximum static levels which would occur in an actual aircraft installation.

5.3 Description of Test Apparatus

The test apparatus for the transducer system consisted of a load test rig and an environmental temperature chamber. Descriptions of each are given below.

5.3.1 Load Test Rig

Figure 12 shows a general arrangement of the load test rig. It consisted of a support base, a loading block, and three spring tensioning mechanisms. The optical transducer was mounted inside a tube which simulated an aircraft axle: the transducer/axle assembly is shown in Figure 13. The axle tube was designed to be removable, so that the transducer could be tested both inside the axle and alone. The assembly was rigidly attached to the support base in a cantilever arrangement, and loads were applied to its free end through the loading block and tensioning mechanisms.

The loads could be applied in three directions simultaneously. These represent the weight on the aircraft tire, lateral forces due to ramps, and longitudinal forces due to brakes. Moving the point of application allowed torsional loads to be applied in combination with longitudinal loads.

Precise measurement of the vertical load was obtained from strain gauges on the loading block. For lateral and longitudinal loads, tension spring deflections gave sufficiently accurate indication of the load level. Measurements of the mechanical behaviour of the sensor tube were made using shear and bending strain gauges mounted on the tube, as shown in Figure 13. The fringe movement which was displayed on the electronic counter, was also visually monitored on an oscilloscope.

5.3.2 Temperature Chamber

An insulated temperature chamber was constructed to determine the effect of temperature on the transducer system. The interior size of the chamber was large enough to contain the transducer tube, fringe generator, load test rig, and heating or cooling devices. The laser, beam-splitting apparatus, and electronic components remained outside the chamber. Holes in the chamber allowed the optical fibres to pass to and from the transducer. The air temperature inside the chamber and the temperature of the loading block were measured using alcohol thermometers.

5.4 Description of Tests

The following static load and temperature tests were performed on the prototype transducer system under controlled laboratory conditions, using the test apparatus described above.

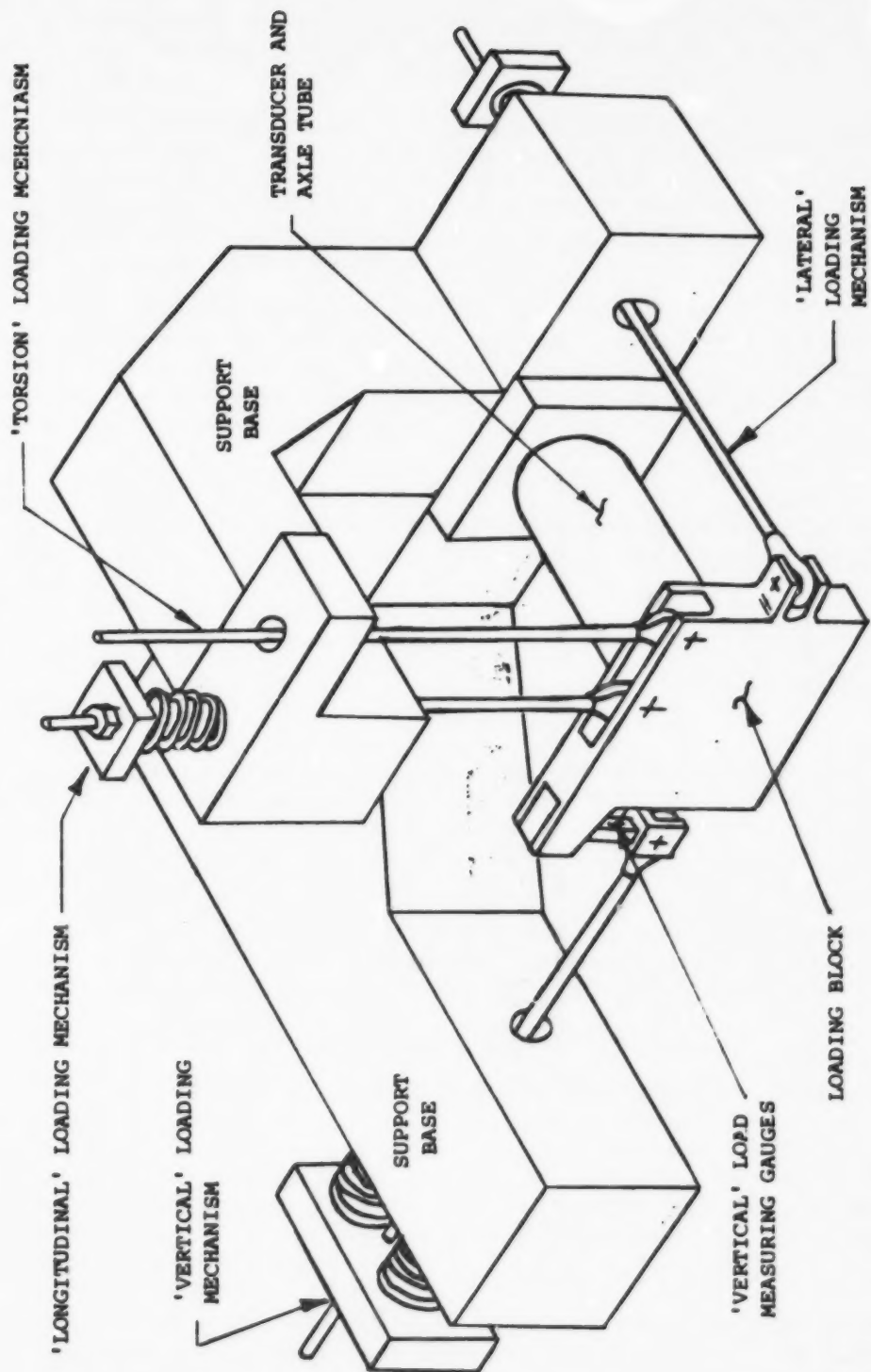


FIGURE 12 TEST APPARATUS FOR LOADING OF TRANSUDER AND AXLE

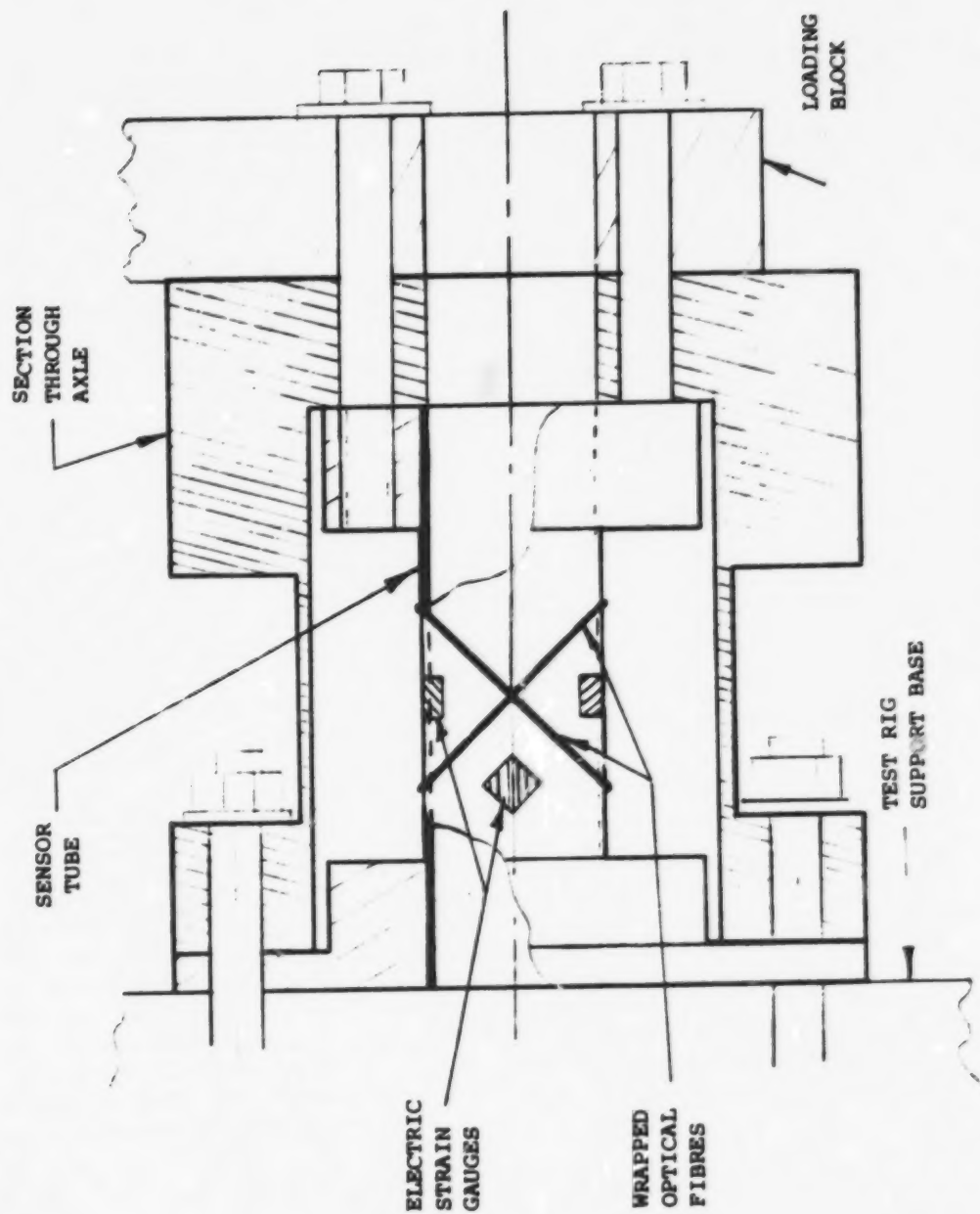


FIGURE 13 PROTOTYPE TRANSDUCER AND AXLE TUBE

- Vertical load measurement
- Immunity to lateral loads
- Immunity to longitudinal and torsional loads
- Immunity to ambient temperature variations
- Immunity to gradient temperatures

For the load tests, two configurations for the transducer were used: (i) transducer alone, and (ii) transducer in combination with the axle tube. Loads were applied in even increments for three load/unload cycles and the output from the transducer (fringe counter) and the electrical strain gauges were recorded.

Because the effects of load and temperature on the transducer are uncoupled *, no loads were applied during the temperature tests. As a result, it was not necessary to test both transducer configurations, and only the transducer tube itself was used.

5.4.1 Vertical Load Conditions

Tests were conducted to determine the following characteristics of the transducer with respect to vertical loads;

- Sensitivity
- Accuracy
- Repeatability
- Linearity
- Hysteresis

For the transducer alone, the maximum applied load was 448 newtons (100 lb) which corresponds to an equivalent shear stress level, as determined by the finite element analysis, or a transducer mounted in the case study axle at a maximum aircraft ramp weight of 18,182 kgs (40,000 lb). For the axle/transducer combination, the maximum vertical load was 806 newtons (180 lb), the limit load of the spring mechanism. This load theoretically produces approximately one third the shear stress in the case study axle at maximum aircraft weight.

5.4.2 Non-Vertical Load Conditions

To determine the influence of non-vertical loads on the transducer output, lateral, longitudinal and torsional loads were applied to the transducer alone, and to the transducer in combination with the axle tube. The maximum non-vertical load levels corresponded to approximately 45% of the maximum vertical loads, and were applied both alone and in conjunction with the vertical load.

* The only coupling between load and temperature is the change in the index of refraction of the fibres with temperature. This effect for a 100°C temperature change, is in the order of a tenth of one percent and can be neglected.

5.4.3 Ambient Temperature Conditions

Ambient temperature effects on the transducer output were examined by placing the mounted transducer tube and load test rig into the temperature chamber and monitoring the transducer output as the temperature was slowly raised and lowered over a range from -18°C to $+22^{\circ}\text{C}$ (using dry ice), and from 20°C to 55°C (using electric heating). The predicted influence of temperature due to unequal lengths of optical fibre was verified by varying the lengths of the free fibre in the chamber.

5.4.4 Gradient Temperature Conditions

To test transducer performance in the presence of a temperature gradient, an electrically-heated power resistor was placed in one end of the sensor tube. Measurements of the surface temperature on the tube were made at four locations to provide an indication of the gradient.

5.5 Discussion of Test Results

In this section, results and observations from the tests conducted on the prototype transducer system are discussed. Graphs of the test data and comparisons with theoretically predicted values are provided in Appendix D.

5.5.1 Vertical Load Measurement

The transducer as tested alone was found to provide a good measure of vertical load. It had a strong sensitivity to the input (86.5 fringes at maximum load), and was in close agreement with theoretical results. There was high linearity in the response and no evidence of hysteresis between loading and unloading.

Repeatability was generally good between load cycles. There was some scatter present in the results, due mainly to the sensitivity of the transducer to environmental disturbances, such as acoustic noise and mechanical vibrations. More importantly, however, there was a drift in the fringe count with time. These effects are discussed further in section 5.5.5 "Optical System Performance". However, as a result of these effects, the desired transducer accuracy of $\pm 1.1\%$ was not achieved. It was determined from the electrical strain gauges that these effects were not due to mechanical behaviour of the sensor tube under load. In fact, the mechanical behaviour was in excellent agreement with results from the finite element analysis.

The results from the combined transducer/axle tests confirmed the theoretical prediction that the sensitivity to vertical load would be reduced by about 70%. The fringe count and strain gauge sensitivities were actually somewhat

larger than those predicted due to the additional elasticity of the bonded and bolted connections which were not included in the finite element model. Since the vertical loads are much higher for an actual aircraft installation than those used in the tests, the reduced sensitivity should not affect the accuracy of the transducer.

5.5.2 Non-vertical Load Immunity

The results from the non-vertical load tests show a good immunity of the optical transducer output to these loads. For the transducer alone there was insignificant sensitivity to longitudinal loads, and only a small sensitivity to lateral and torsional loads. These sensitivities were difficult to quantify precisely due to the presence of drift in the fringe count signal. However, on average, they seem to be in the order of one to three fringes at maximum load. There was even less sensitivity in the combined transducer/axle tests due to higher stiffness of the axle.

The sensitivity to lateral loads was caused by asymmetries in the two fibre paths on the sensor tube as a result of the wrapping and bonding procedures used. For instance, since one fibre overlaps the other at the crossover point of the fibre pattern, the two fibres do not experience the same strain under lateral loads. Hence there was incomplete cancellation of the change in path length between the two fibres; this can be overcome by slight changes in the winding pattern.

The sensitivity to torsion loads was due to the discontinuity of the bonded fibre pattern at its start-and-stop position on the sensor tube. Complete cancellation of torsional strains within a single fibre was required for no torsional sensitivity. However, since no fibre strains existed at the start-and-stop location, but did occur at the crosspoint on the opposite side of the tube, the fibre pattern was unbalanced, and as a result, the transducer was slightly sensitive to torsional loading. As for the lateral case, torsional load sensitivities can be decreased or eliminated by slightly modifying the fibre pattern.

5.5.3 Effect of Variations in Ambient Temperature

The prototype transducer showed some sensitivity to variations in temperature. This sensitivity which ranged from 0.3 to 1.7 fringes/°C, was found to be highly dependent on: (i) the difference in length of the unbonded sections of the two single-mode fibres which were exposed to the temperature variations, and (ii) the difference between ambient and transducer temperatures. The sensitivity to the latter was due to different thermal coefficients of expansion for the bonded and unbonded portions of fibres.

For fixed test conditions, the sensitivity to gradual temperature changes was linear and repeatable. Short term deviations from linearity coincided with disturbances in the test conditions, such as variations in the power level to heat the chamber, or opening the chamber to allow cooling. These disturbances created variations in temperature within the chamber due to conduction and convection, which subjected the unbonded portions of the fibres to differing temperatures along their lengths, and as a result, deviations from linearity.

These temperature sensitivities were due to the lack of a splitter/coupler and to the manual fibre winding procedure used. With more fully developed optical components and refined fibre winding, it should be possible to control the difference in length of the optical fibres so that the temperature sensitivity is reduced to acceptable levels.

5.5.4 Effects of Temperature Gradients

During these tests there was a decrease of 12 fringes for a 10°C difference between the two ends of the sensor tube. This change in fringe count was due to a number of sources. For example, there was asymmetry in the unbonded portions of the fibres along the sensor tube due in part to the space requirements of the electrical strain gauges. As heat was applied to the sensor tube, these unbonded sections experienced differential temperatures. Also, a slight difference in lengths of the bonded fibres would cause a sensitivity to the average temperature of the tube.

It was not possible to separate and quantify these effects in the prototype transducer, so that the actual sensitivity of the bonded fibres to temperature gradients could not be determined. In any case, a need exists to quantitatively evaluate temperature gradients in the aircraft axle environment; this is further addressed under "Recommendations" (section 7).

5.5.5 Optical System Performance

The transducer output was found to be affected by various environmental disturbances which were present from time to time during the tests. Acoustic noise and mechanical vibration caused the fringe pattern, and hence the fringe count, to oscillate at the various resonant frequencies of the optical bench and beam-splitting apparatus. While bothersome for reading the fractional counter, these disturbances were transient and did not generally affect the accuracy of the output.

A more serious problem was low frequency oscillation or "rolling" of the fringe pattern which was present during the tests to varying degrees up to a maximum deviation of 2 fringes. This phenomenon, while not completely understood,

was attributed in part to small air currents around the test apparatus. Shielding of various components of the transducer, and in particular, the loose fibres and sensor tube, was found to reduce the amount of rolling.

In some of the load tests, a long term drift in the fringe pattern was observed. The magnitude of the drift varied from test to test and ranged from approximately 4 fringes per hour to no apparent drift. No single cause for this drift could be determined, and it is believed to be the result of a number of factors; for example: changes in the ambient conditions (temperature, pressure, and humidity) which affect the wavelength of the light through the air; and mechanical drift of the components in the beam-splitting apparatus due to mechanical and acoustic vibrations. It should be possible to eliminate rolling and drift by using a fully developed splitter/coupler.

It was known that changes in stress and temperature can affect the state of polarization of light propagating in single-mode fibres, and as a result, affect the fringe pattern contrast in the fringe generator. The presence of this phenomenon was confirmed by the observation of occasional dips in the level of the counter input signal during the tests. Typically one dip would occur over the range of vertical loads; and two to three over the range of temperature tests. They seldom occurred during the non-vertical load tests since both fibres were subjected to similar strains. These variations in fringe contrast were generally not a problem for the electronic counter, except when the contrast became so low that the fringe pattern became undetectable. The changes in polarization state can be eliminated if single-mode fibre having polarization-maintaining characteristics is used.

Since the single-mode fibre connectors were not used in the actual sensor system tested, a separate evaluation of them was performed in terms of their ease of assembly and disassembly. They were found to be excellent in this respect, and no significant loss of light was perceived. Quantification of the loss has been conducted by others (6), and was not repeated by DSL.

5.5.6 Electronic Counter Performance

As described in section 3.2.3, the electronic counter showed excellent performance when electrical signals were used to simulate the output from the fringe generator and photodiodes. Resolution and accuracy were 0.01 and ± 0.01 fringes respectively with input signal levels of less than 50 millivolts peak-to-peak.

However, due to the exceptionally high optical losses in the beam-splitting arrangement for the prototype transducer, the photo-diode amplifier gains had to be increased with a consequent decrease in signal-to-noise ratio. Also, inaccuracy in the construction of the breadboard fringe generator resulted in considerable deviations from the optimum 90° phase difference between pickup fibres. These two problems caused some degradation in counter performance; for example: 100 mV input signals were required for a reliable integer count; and 500 mV for the fractional count (the nature of the fractional counter makes it more sensitive to phase difference errors).

It was also found that false triggering of the integer count could occur during rapid changes in the amplitude of the optical signal within one fringe movement (as a result of mechanical vibrations within the beam-splitting arrangement). Consequently, the counter was modified to increase the hysteresis in the input comparator circuit; this cured the false triggering. This problem is specific to the prototype; there is no doubt that, with a proper splitter/coupler and fringe generator, the original design will perform to specification.

5.6 Summary of Results

The results from the static load and temperature tests performed on the laboratory prototype optical weight sensor system are summarized below:

1. Generally, the system was found to meet the design objectives of measuring vertical load with little sensitivity to non-vertical loads.
2. The system demonstrated excellent vertical load measuring capability with high sensitivity and linearity, good repeatability, and no hysteresis.
3. Both the fringe count and strain gauge outputs showed good agreement with predicted values from the finite element analysis of the sensor tube.
4. Slight sensitivities to non-vertical loads were determined to be the result of the winding and bonding procedures used, and can be eliminated with refined techniques.
5. No unexpected behaviour was initiated by installation of the transducer into the simulated axle. Deviations from theoretical behaviour are due to the elasticity of the connections between the sensor and axle.
6. Because of the "breadboard" arrangements for the splitter/coupler and fringe generator, the system was

sensitive to temperature changes and to environmental disturbances such as acoustic noise and mechanical vibrations. With proper optical components these effects can be reduced to acceptable levels.

7. There is some sensitivity to temperature gradients along the sensor tube. However, due to the nature of the tests and the configuration of the prototype, the sensitivity of the bonded fibres could not be quantified.
8. The fringe pattern contrast was found to be affected by changes in load and in temperature due to changes in the state of light polarization in the two fibres.
9. After modifications were made to the electronic counter to account for the higher optical losses in the bread-board splitter/coupler, the counter provided an accurate and reliable measure of the fringe count. Errors in the electronic count only occurred due to the polarization effect described above.

6. CONCLUSIONS

In this project, a fibre optic weight sensor was designed and developed for use as an element in an on-board aircraft weight and balance system. A prototype version of the sensor was constructed and tested under controlled laboratory conditions. Specific conclusions resulting from this project are:

1. From a review of existing and proposed standards, and a survey of various aircraft manufacturers and operators, the SAE recommended practice ARP 1409 for an on-board aircraft weight and balance system was found to be an acceptable basis for the establishment of the "general requirements" document for an aircraft weight-sensing transducer.
2. The establishment of specific accuracy requirements for transducers for the nose and main gears of the case study has demonstrated that achievable transducer requirements can be defined to meet the overall system accuracy requirements of ARP 1409. The establishment of these requirements is a significant advance in the development of a sensor.
3. A design for the weight sensor comprising optical, mechanical, and electronic components has been achieved which meets the accuracy requirements for the case study axle.
4. A methodology using finite element modelling has been developed for evaluating the mechanical configuration of the sensor and optical fibre pattern. This methodology can be applied to a variety of axisymmetric axle geometries and has been verified against the test results of a laboratory prototype transducer.
5. The laboratory prototype optical weight sensor demonstrated good performance with accurate measurement of vertical load, and good immunity to non-vertical loads.
6. The system's sensitivity to environmental and temperature effects is understood, and can be eliminated with the use of more fully developed optical components.
7. The tests on the prototype sensor have confirmed the design principles of many components; namely: the sensor tube and fibre configurations; the selection and handling procedures of single-mode optical fibres; the

selection of multi-mode pickup fibres; and the design of the electronic counter.

8. Discussions with various suppliers of fibre optic hardware indicate that many of the components for the weight sensor are now commercially available, and that because of current development work for military and civil aircraft applications, versions suitable for in-aircraft transducers should be available shortly.

7. RECOMMENDATIONS

The results from this project have demonstrated that a weight sensing transducer system with good measurement characteristics can be constructed using fibre optic technology. Before such a system can be used for an aircraft application, however, additional development remains to be done. As a result, the following recommendations for future work are made:

1. The investigation into the availability of optical components suitable for in-aircraft transducers must be pursued, particularly with regard to the splitter/coupler, fringe generator, and polarization-maintaining single-mode optical fibres. These investigations must address the packaging and miniaturization of the sensor-mounted components. Since the fringe generator is specific to the optical weight sensor, development will be required. The availability of appropriate laser diodes, (i.e. those with a stable frequency), also needs to be investigated.
2. The demonstration of the survivability aspects of optical components such as the fibre cables and connectors, needs to be performed. Such a demonstration can be achieved by installing these components on an actual aircraft and periodically monitoring performance over a large number of take-off and landing cycles. In addition, the survivability of bonded optical fibres under dynamic load and temperature conditions needs further examination.
3. A detailed design for the mechanical sensor and its mounting in an actual aircraft axle is needed. Construction, installation, and testing of the design must then be performed to determine its reliability under actual aircraft conditions.
4. Development of fibre winding and fibre trimming techniques is needed in order to ensure the required immunity to non-vertical loads and temperature changes. If smaller diameter single-mode optical fibres are to be used for miniaturization, the fibre handling procedures will need to be reviewed.
5. The influence of temperature gradients in aircraft axles on the performance of the sensor system needs to be examined. To achieve this, work is required in two areas. The first is to quantify actual temperature gradient profiles found in the aircraft axle environment, either through tests or through theoretical studies. The second is to modify the existing sensor system using proper optical components and to test it under known temperature gradient conditions.

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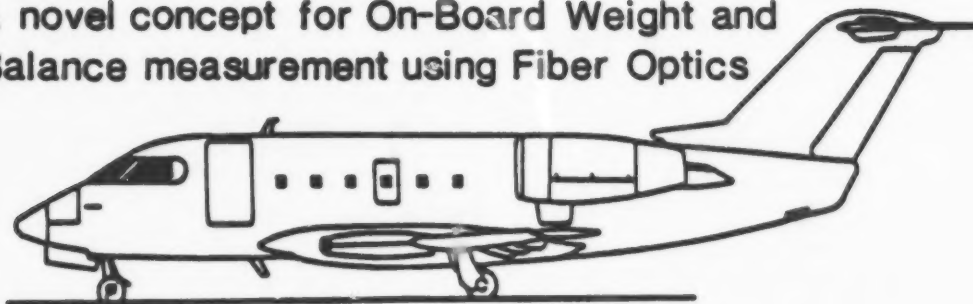
APPENDIX A

THE LIGHT-WEIGHT SYSTEM



THE "LIGHT-WEIGHT" SYSTEM

A novel concept for On-Board Weight and Balance measurement using Fiber Optics



by

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This paper describes recent theoretical and experimental work carried out by DSL Dynamic Sciences Limited, in an effort to develop an onboard weight and balance system (OBWB) suitable for small transport aircraft such as the Canadair "Challenger" and the De Havilland "Dash 7".

The work was instigated and funded by Transport Canada Research and Development Centre, in response to Canadair's failure to locate a supplier of an OBWB for the Challenger - available systems either experienced problems of accuracy and repeatability, or were unsuitable for small aircraft.

Dynamic Sciences developed a concept for solving these problems by using optical transducers to detect deflections inside the landing gear axles. Such transducers would be electrically passive, highly sensitive to deflections and lightweight.

The optical technique chosen was the 'fiber optic strain gauge', which operates on the principle that light takes a longer or shorter time to pass through a glass fiber which is stretched or compressed. An interferometer incorporating this technique was constructed, and it was demonstrated in the laboratory that such a system is capable of measuring deflections of axles on small transport aircraft to the required accuracy.

A preliminary design for an aircraft weight sensor based on this fiber optic technology was produced and presented to the Canadian aircraft manufacturers, who concluded that it was practicable.

The sensor consists of a hollow tube to which glass fibers are bonded. The fibers are bonded in such a way that the sensor is sensitive only to vertical shear due to vertical load. Two such tubes are mounted inside each axle. Light from a laser inside the aircraft is fed by glass fibers to each sensor tube. An interference pattern, produced by the fibers bonded to the tube, is transmitted by a fiber bundle to a fringe counter located inside the aircraft. The fringe counters provide inputs to a digital computer which computes and displays the aircraft's gross weight and centre of gravity location.

The next stage in the development of the 'Light-Weight'

OBWB system will be the production of an experimental optical transducer system and its calibration under controlled laboratory conditions.

1. INTRODUCTION

1.1 BACKGROUND

Onboard weight and balance systems have existed since the early sixties.

The main difference between such systems has been the type of transducer used. The transducers have always been located in or on the nose and main landing gears, and one of the following two approaches has usually been taken:

- Pressure transducers inside each oleo strut of the landing gear, e.g.
 - Fairchild 'STAN' system
 - Canadian Marconi Company system
- Electrical strain gauge transducers to measure shear strain, either
 - inserted into each axle, (e.g. BLH Electronics Inc. 'OBAWS')
 - bolted onto mounting lugs, integral to axles and bogie beams (e.g. Electro Development Corporation system for the Lockheed L1011).

Both approaches have experienced problems which have obstructed their certification as primary dispatch systems, relegating them normally to reference systems only.

The main problems can be summarized as follows:

- Oleo pressure systems - friction inside oleo struts
- Strain gauge systems - amplifier drift and high noise to signal ratio

The Dynamic Sciences concept avoids these problems by following the strain gauge approach, but using optical, instead of electrical, strain gauges.

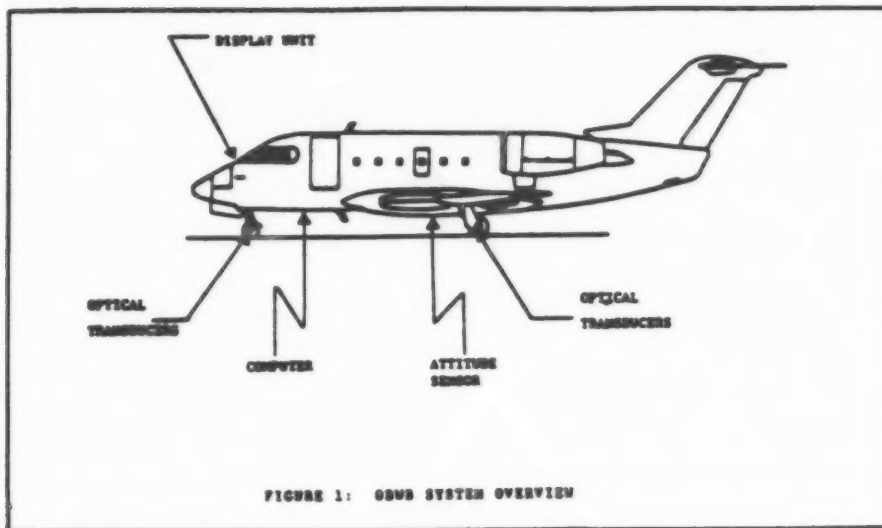


FIGURE 1: OBWB SYSTEM OVERVIEW

The optical transducer is inherently digital. This brings the following advantages at a system level:

- a) Infrequent calibration
- b) Automatic error detection can be carried out on a major portion of the system
- c) The range can be easily extended to include the full dynamic range (e.g. for hard landing detection) without sacrificing resolution and accuracy over the normal working range.

Optical components and cables in general weigh considerably less than their electrical equivalents; for this reason, the 'Light-Weight' OBWB system is expected to provide the additional bonus of weight saving.

2. OPTICAL TRANSDUCER

Dynamic Sciences' analysis of the problems experienced by previous and current systems favoured the attempt to detect deflections inside the landing gear axles, but concluded that optical sensors should be used instead of electrical strain gauges. The main advantage of an optical sensor is that, being electrically passive, it does not generate electrical noise, nor is it sensitive to, for instance,

- radio frequency interference
- cross-talk
- thermo couple effects
- leakages to ground

which contribute to the problems experienced by strain gauge systems.

1.2 THE LIGHT-WEIGHT OBWB SYSTEM

The essential components of the system are illustrated in Figure 1. They are:

- Optical transducers (two per axle)
- Attitude sensor
- Computer
- Display unit

The optical transducers provide digital inputs to the computer corresponding to the vertical wheel-loads. Through calibration, the relationship between these digital values and wheel-loads is established.

The attitude sensor provides an input to the computer system, which is used to compensate for ramp angle.

The computer uses the inputs from the optical transducers and attitude sensor to continuously compute the aircraft's gross weight and centre of gravity location which it outputs to the display unit. Having two transducers per axle enables the computer to detect, and report, differential wheel-loads caused for instance by uneven tire pressures.

Figure 2 is a block diagram of a single optical transducer. The laser and fringe counter are located, with the computer, inside the aircraft. The splitter/coupler and fringe generator are attached to the sensor which is located inside the axle.

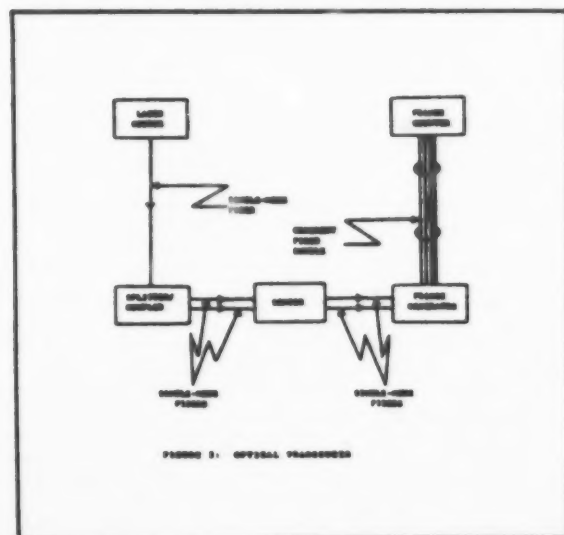
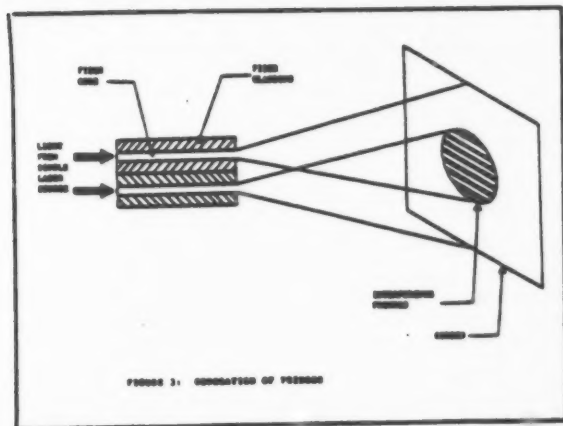


FIGURE 2: OPTICAL TRANSDUCER



Single-mode fiber has a very small core (2 to $8 \times 10^{-6}\text{m}$ (100 to $300 \times 10^{-6}\text{in}$); since the smallness of the core radius approaches the wavelength of the laser source, only a single mode is propagated (only one light ray can pass through the core). The splitter/coupler is a device which splits the light received from a single input fiber equally into two output fibers. The fringe generator is a special optical device which is described later in this paper. The coherent fiber bundle is a group of fibers arranged such that an image formed on the input face is seen on the output face. The fringe counter is a special electro-optical device which follows the movement of interference fringes and maintains a count of the number which pass a fixed point.

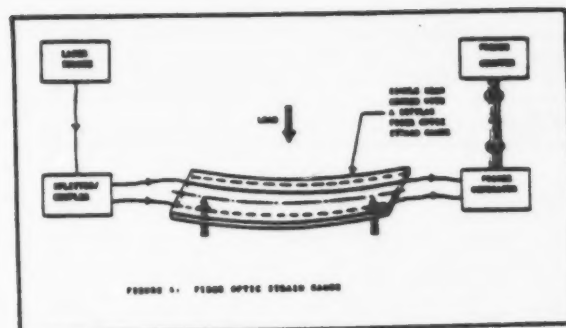


2.1 FIBER OPTIC STRAIN GAUGE

The device chosen for the optical transducer was the fiber optic strain gauge (Ref. 1). Whereas electrical strain gauges rely on variations of electrical resistance as the gauge is stretched or compressed, the fiber optic strain gauge uses the principle that light will take a longer or shorter time to pass through a glass fiber that is stretched or compressed. If two optical paths are used, the light emitting from the two fibers can be made to interfere producing fringes, as shown in Figure 3 - these fringes move as the difference in optical path lengths changes.

Figure 4 illustrates how the principle of the fiber optic strain gauge may be applied to the measurement of the bending of a simple beam.

- Coherent monochromatic light generated by a laser is coupled into a single mode fiber;
- at the beam, the fiber is split into two single mode fibers (each taking approximately 50% of the light);
- one fiber is bonded to the top of the beam, and the other is bonded to the bottom of the beam, providing a push-pull effect;
- the two fibers enter a fringe generator, in which the ends are bonded side by side such that the light emerging from the two ends interferes;
- part of the resulting fringe pattern is captured in a fiber bundle, and transmitted thereby to an up/down fringe counter.



If a load is applied to the centre of the beam such that the beam bends, the fiber running along the top of the beam will be compressed, and the fiber running along the bottom of the beam will be stretched. The change in the difference of the optical path lengths through the two fibers produces a displacement of the fringes - the number of fringes which pass across the fixed point provides a digital measure of this change, which is directly related to the deflection of the beam.

This arrangement automatically compensates for temperature changes. Both optical paths are affected equally, and there is no net displacement of fringes due to temperature.

2.2 ADVANTAGES

In addition to being electrically passive, such an optical transducer has the following advantages:

- Digital - the output (fringes) is digital, removing the need for A/D conversion for input to a computer system.
- Sensitivity - movement of one fringe past a fixed point occurs for a net change in optical path of one wavelength of the light used, (approximately 0.6×10^{-6} metre, or 25×10^{-6} inch, for a HeNe laser).

This sensitivity can be increased, if required, by

- multiple looping of the fibers;
- counting sub-multiples of fringes.

- Insensitivity to connecting cable effects - the inter-connecting cables cannot contribute to (and therefore obscure) the effect to be measured. Changes in the intensity of light passing through the input cable (caused, for instance, by temperature changes) will not cause fringe shifts and, since the fringes are generated at the sensor, the output cable cannot cause fringe shifts either.

- Low power consumption - it is estimated that the optical transducer (including laser and fringe counter) will consume approximately 1 watt.

3. EXPERIMENTAL VALIDATION

Experimental validation of the principle of the fiber optic strain gauge was carried out using the simple set-up shown schematically in Figure 5.

A laser light source was focused by a microscope objective lens onto the ends of two single mode fibers bonded side by side. A section of one of the fibers, from which the protective coating had been removed, was bonded to the top

surface of the beam, while the other fiber was left free. The other ends of the two fibers were held side by side and a photo-diode array was positioned in the interference pattern, so that the motion of the fringes could be observed on an oscilloscope.

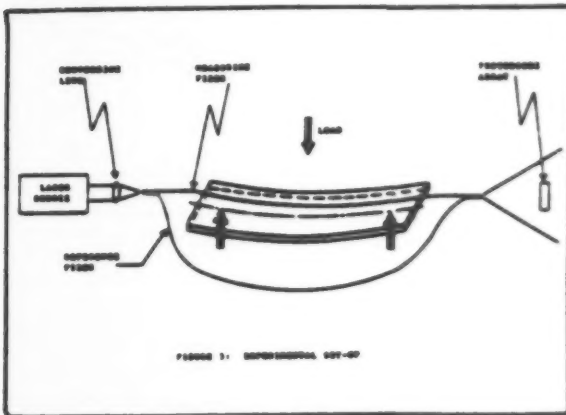


FIGURE 5: EXPERIMENTAL SETUP

The mid-point of the beam was deflected by a screw jack and lever. The deflection was measured by a dial gauge placed in proximity to the load application point, and the number of fringes moving past a fixed point on the oscilloscope screen was counted.

The results obtained are shown in Figure 6. A movement of one complete fringe required a deflection of 6×10^{-6} metre (250×10^{-6} inch). The errors shown are believed to be primarily a result of the attempt to measure minute deflections with relatively simple equipment which caused tilting of reference surfaces and slippage of mechanical parts.

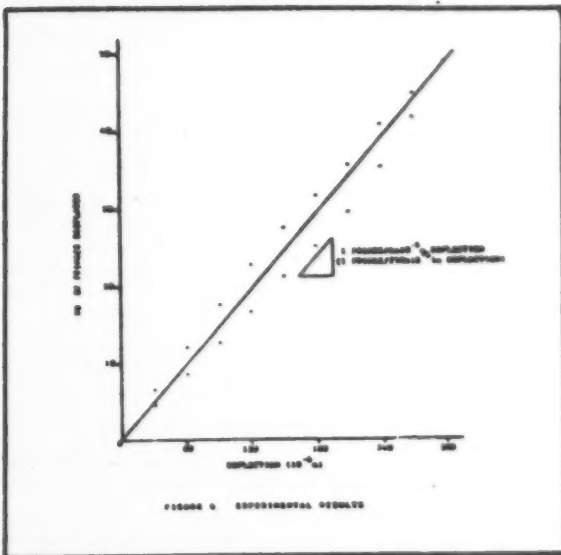


FIGURE 6: EXPERIMENTAL RESULTS

4. PRELIMINARY DESIGN OF SENSOR

The preliminary design of a sensor for the Canadair "Chal-

lenger" and the De Havilland "Dash 7" was based on the following considerations.

The axle, as a beam, is subject to the following deflections:

- vertical shear due to vertical load
- bending due to vertical load and side load
- torsion due to wheel drag
- longitudinal deflection due to side load

The design of the sensor must be such that it is sensitive only to vertical load; therefore it must be sensitive only to vertical shear.

Figure 7 illustrates the effect of vertical shear on an axle under load. It also shows how the 'bending' sensor shown in Figure 4 can become a shear sensor by the simple expedient of swapping over the optical paths at the mid-point of the beam; such a sensor will be insensitive to:

- bending
- torsion
- longitudinal compression or tension

Since the load on the axle may be unevenly distributed between the two wheels (due for instance to different tire pressures), two shear sensors are required, one for each wheel.

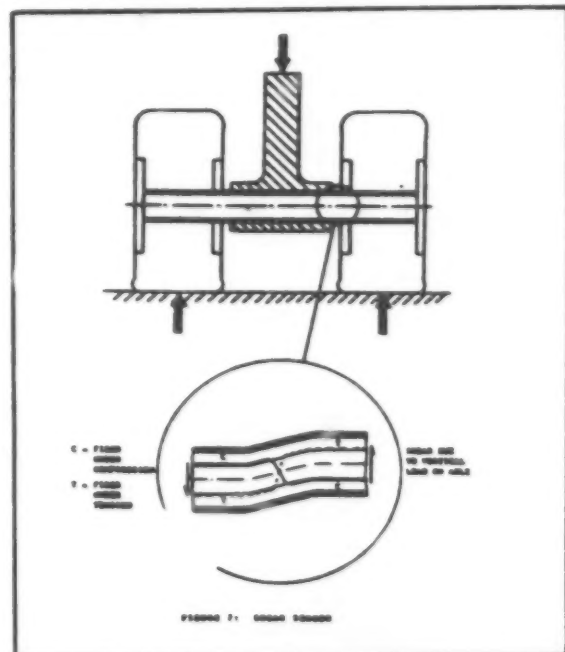
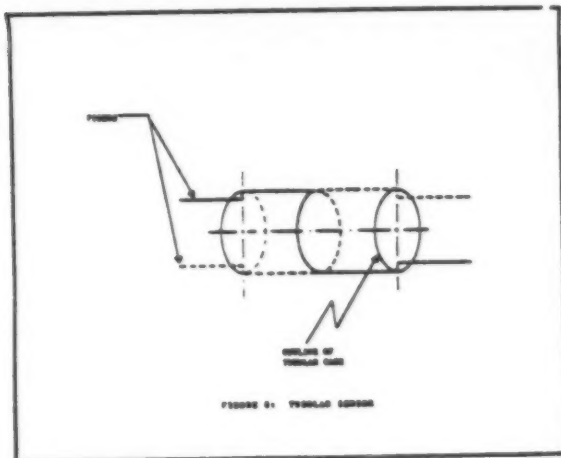


FIGURE 7: DESIGN DIAGRAM

4.1 PHYSICAL CHARACTERISTICS OF SENSOR

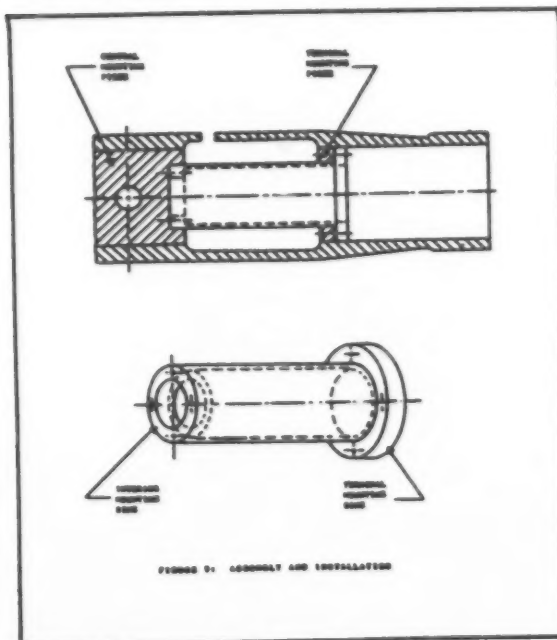
To duplicate the deflection pattern of the axle, the sensor has to be clamped to the axle at least at both ends. To allow for changing temperatures, the sensor should be made of the same material as the axle. It should also be of maximum depth, but minimum stiffness.

A serious problem that had to be contended with in the main gear axles was the anti-skid devices which intrude into the regions of most significant shear.



These reasons led to a design which required the sensor to be in the form of a hollow tube. The anti-skid device could then protrude partly inside it.

Another serious problem was the cables which attach to the anti-skid devices - these enter the axle either through a hole at its centre or through two holes on either side. For this reason, the tube had to be a tubular cage to allow these cables to pass through it - this has the added advantages of lightness and reduced stiffness. The resulting sensor is illustrated in Figure 8.

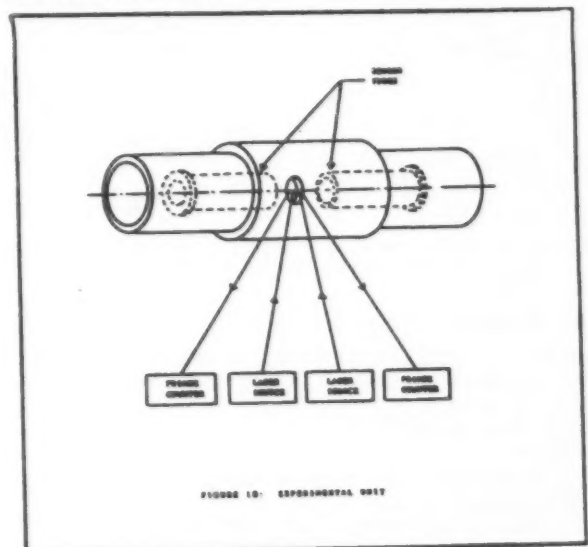


4.2 ASSEMBLY AND INSTALLATION

The sensor is completed by the incorporation of mounting rings at each end.

Figure 9 shows one of the sensors installed by being slid in and screwed into place.

When the experimental unit has been assembled, it will be installed in a landing gear axle (see Figure 10) and subjected to a series of tests. A vertical load calibration test will quantify its ability to measure vertical loads and enable an assessment of sensitivity, repeatability, linearity, etc. Further tests will establish the sensitivity of the transducer to axle rotation, side loads and torsion.



The inner end of the sensor tube is fixed to a central mounting piece; the outer end of the sensor tube is fixed to a terminal mounting piece. Both mounting pieces can be bonded to the inside surfaces of the axle without modification of existing axles (a preferred approach is to have these mounting pieces appearing as integral features of the axle in future designs). The sensor tube can be simply removed for service or inspection. For the main gears, the optical cables will enter and exit the axles through the same holes as the anti-skid device cables. Similar holes will be required for the optical cables to enter and exit the nose gear axle.

5. FURTHER DEVELOPMENT

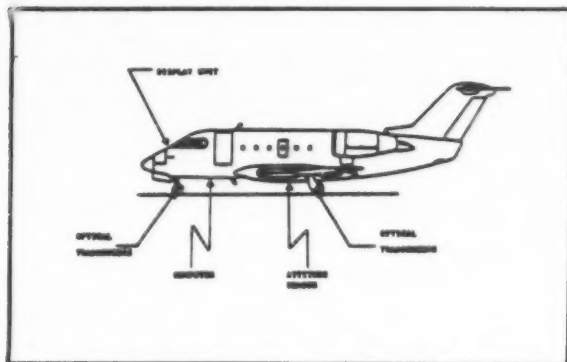
Subject to the approval of the Transport Canada Research and Development Centre, Dynamic Sciences will soon embark on the next stage of development of the onboard weight and balance system based on the preliminary design concepts described in this paper.

The immediate task will be a detailed design effort leading to the fabrication of an experimental unit, and its calibration under controlled laboratory conditions.

6. ACKNOWLEDGEMENTS

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port Canada Research and Development Centre (TDC) and the assistance and encouragement of the TDC project officer, Mr. D. Hanchet. We also acknowledge the advice and cooperation provided by personnel of the ITT Electro-Optical Products Division, and E. G. and G. Reticon.



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APPENDIX B

GENERAL REQUIREMENTS FOR A WEIGHT-
SENSING TRANSDUCER FOR AN ON-BOARD
AIRCRAFT WEIGHT AND BALANCE SYSTEM



GENERAL REQUIREMENTS FOR A WEIGHT-SENSING
TRANSDUCER FOR AN ONBOARD
AIRCRAFT WEIGHT AND BALANCE SYSTEM

Interim Information Report
prepared for
Transport Canada
Transportation Development Centre

Contract file 09SD.T8200-0-0543
Contract serial LSD81-00085

DSL Dynamic Sciences Limited
St-Laurent, Que.

Report C162-01
March, 1982

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1.0 INTRODUCTION

In January 1978, the Society of Automotive Engineers (SAE) released Aerospace Recommended Practice ARP 1409 pertaining to "Requirements for Aircraft Onboard Weight and Balance System". The purpose of this document is to establish requirements for the function, characteristics and installation of an onboard aircraft weight and balance system (AWABS)¹. for "primary use on civil transport aircraft".

The Society of Allied Weight Engineers (SAWE) is also preparing their own aerospace recommended practice document for AWABS. The ARP is based on the SAE document, but contains major revisions to many of the requirements. To date, the SAWE ARP is only in draft form and has not been approved by the Board of Directors of the SAWE.

As part of the work to develop a fiber optic weight sensor for AWABS, a set of requirements for the weight-sensing transducer and the transmission of signals to and from the transducer was to be derived. To accomplish this, DSL Dynamic Sciences Limited has reviewed both the SAE and SAWE documents, and has surveyed operators and manufacturers in the aircraft industry about items in these documents concerning the transducer.

This report describes the work performed and provides a list of requirements for an AWABS transducer.

-
1. In this report, the acronym AWABS will be used exclusively. Other acronyms, such as OBWBS which are found in the literature, are replaced by AWABS.

2.0 DESCRIPTION OF WORK

2.1 REVIEW OF ARP DOCUMENTS

The ARP 1409 document of the Society of Automotive Engineers was examined by DSL. Relevant paragraphs of the ARP concerning the requirements for an AWABS weight-sensing transducer were noted, and pertain to the following areas:

- (i) Range of Operation for determination of
 - Weight
 - Centre of Gravity
 - Lateral Centre of Gravity
- (ii) Accuracy for determination of
 - Weight
 - Centre of Gravity
 - Lateral Centre of Gravity
- (iii) Compensation for
 - Application of Brakes
 - Temperatures as a result of braking
- (iv) Weight of System
- (v) Compatibility with other Aircraft Components
- (vi) Environmental and Functional Requirements
- (vii) Cyclic Loading Requirements

(viii) Maintainability and Reliability Requirements, and in particular,

- Component replacement
- Calibration
- Adjustment
- Interchangeability

These items form the basis for the list of requirements for an AWABS transducer given in section 3.0 of this report.

The SAWE draft ARP document of 13 May, 1980, was also reviewed by DSL. The intent of this document is the same as that of the SAE ARP, in that it defines a set of requirements for an onboard weight and balance system. The document is, "in major part, a revision to Aerospace Recommended Practice 1409". Roger Bullock, who is co-chairman of the SAWE committee to review, modify and approve this specification, was contacted to determine the status of the ARP. As of March 1982, it was still not approved. The ARP is presently a low priority item for the SAWE, although there may be some discussion on this subject by SAWE members prior to their May 1982 annual conference.

2.2 SURVEY FOR COMMENTS

Based on the review of the ARP documents, DSL prepared written questionnaires to 12 aircraft operators and 10 manufacturers, concerning requirements for a transducer for an onboard weight and balance system. The list of 22 companies contacted is given in Appendix A. The purpose of the questionnaire was to obtain information on:

1. Their comments to the ARP requirements.
2. Specific data on their aircraft to ensure the design of the weight-sensing transducer would be applicable to a wide range of aircraft in service.

The questions related to items (i) through (viii) as given in section 2.1 of this report, and were based on the SAE specification. (The SAWE document was not used because it is in a draft form only).

Two questionnaires were used: one for operators, the other, for manufacturers. Appendix B includes sample letters and questionnaires to an operator and to a manufacturer.

From these companies, sixteen responses were received. Four airlines provided comments to the questionnaires, while two airlines stated that they had no interest in AWABS. Four manufacturers provided information on their aircraft, while two others did not provide data because they had no need for AWABS. Another manufacturer did not provide data due to the work involved. Two airlines and one manufacturer have not, as yet, provided data because of heavy work loads, but plan to send information when time permits.

Their responses are briefly discussed below. In general, it was found that the requirements given in ARP 1409 are acceptable as they stand.

In terms of range of operation, the specified values for weight and centre of gravity in the ARP meet the conditions for all operators. The accuracy values were also found acceptable to all the respondents, though two of them stated that a greater accuracy on centre of gravity determination ($\pm 0.5\%$ instead of $\pm 1.0\%$) would be desirable. In terms of the loading requirements, one airline thought that rather than the limits given in the ARP, the transducer should withstand any load imposed on it up to the design limit of axle to which it would be attached.

From the responses to the questionnaire regarding cyclic loading, it was found that, for medium and long-range aircraft, the specification of 15000 landing cycles would exceed the overhaul period for the landing gear itself.

Because only a small number of respondents provided comments on the ARP, the information obtained was not considered adequate for DSL to recommend changes to the requirements in ARP 1409.

However, the responses have highlighted other important points for a potential AWABS transducer. These were:

1. The transducer and system must overcome the lack of reliability that has been exhibited by existing AWABS hardware.
2. Pre-departure planning of aircraft loading is still required for aircraft having an AWABS installed. It was suggested that the main task of the system would then be to verify the pre-departure planning.
3. Because of unique loading problems, there may be a greater need for an AWABS on cargo aircraft than on passenger aircraft.

The results of the survey confirmed DSL's observations that an AWABS can offer distinct advantages over conventional systems using aircraft and manifest weight data only. For example:

1. An AWABS will provide data on the actual weight and balance of an aircraft which, under snow and icing conditions, will include the added weight of the ice and snow. Systems relying on aircraft and manifest data only cannot measure these effects.
2. Periodic reweighing of the aircraft to determine changes in aircraft empty weight can be eliminated.
3. An AWABS will contribute to savings by simplifying or eliminating "late load adjustments" for aircraft weight and balance which are currently necessary.
4. The weight and balance data from an AWABS is based on actual passenger and carry-on baggage weight. Conventional systems use only statistical averages for these weights.

3.0 LIST OF REQUIREMENTS

The following is a list of requirements for a weight-sensing transducer for an onboard aircraft weight and balance system. In most cases the requirements are taken directly from the SAE document ARP 1409 without any changes, except for re-numbering and to make the requirement specific to the transducer rather than the system.

In certain areas, the ARP requirements pertain to electrical transducers only, and not to optical sensors. These items have been deleted from the requirements below as they are not applicable to an optical transducer.

In addition, the paragraphs of the ARP concerning environmental requirements for the transducer and cables have been explicitly identified.

REQUIREMENTS

The transducer shall enable the system to determine actual aircraft weight and center of gravity according to paragraphs 3.1 to 3.3.

3.1 RANGE OF OPERATION

3.1.1 Weights

The system shall determine and display the aircraft weight throughout a range from 10% less than aircraft empty weight to 10% greater than maximum taxi gross weight.

3.1.2 Center of Gravity

The system shall determine and display the aircraft center of gravity throughout a system range determined as follows:

Determine aircraft maximum center of gravity range expressed in Percent Reference Chord such as Mean Aerodynamic Chord (MAC) or equivalent by subtracting most forward limit from most aft limit. Extend most forward aircraft limit forward by an amount equal to 50% of the aircraft range, but not exceeding the forward point equivalent to zero MAC. Extend most aft aircraft limit aft by an amount equal to 50% of the aircraft range, or to the static aft tipping point, whichever is further aft.

3.1.3 Lateral Center of Gravity

Where required for a specific aircraft usage the system shall be capable of determining the lateral center of gravity of the aircraft throughout a symmetric envelope 10% greater than the aircraft certified lateral center of gravity limits.

3.2 ACCURACY

The system shall be capable of determining and displaying aircraft weight and center of gravity within $\pm 1.0\%$ of actual aircraft weight and $\pm 1.0\%$ Mean Aerodynamic Chord. Lateral center of gravity if required shall be determined and displayed within $\pm 1\%$ of the lateral center of gravity range.

3.3 MODE OF OPERATION

The system shall determine the aircraft weight and center of gravity in the ground static mode and shall compensate for the following factors.

- Aircraft brakes locked or released.
- Landing gear steering set for zero to minimum turning radius.
- Aircraft brakes at ambient or at maximum temperatures permitted for dispatch.

3.4 WEIGHT

The transducer weight shall be minimized consistent with function, maintenance and reliability requirements. The transducer weight shall be such that the total weight of the system, less connecting lines or cables, shall not exceed 50 lb (22.8 kg).

3.5 COMPATIBILITY^{1.}

There shall be no structural, functioning, or servicing interference between the transducer and any other aircraft system or component, whether the transducer is operating, not operating, or has experienced any failure mode to be expected in service. The transducer design shall provide protective devices to insure it offers no mechanical hazard with the transducer operating, non-operating or in any normal failure mode.

3.6 ENVIRONMENTAL AND FUNCTIONAL REQUIREMENTS^{2.}

The transducer and cables shall meet the following requirements of Radio Technical Commission for Aeronautics Document No. DO-160, "Environmental Conditions and Test Procedures for Airborne Electronic/Electrical Equipment and Instruments", dated 28 February, 1975:

1. From the ARP compatibility requirement, the references to "no electrical interference", and "no electrical or explosive hazard" have been deleted since they are not applicable to an optical transducer. Also the requirement that the transducer "shall be protected from any electro-magnetic interference" has been deleted.

2. The requirements of DO-160 dealing with the following aspects have not been included in this list of requirements, as they do not specifically apply to the optical transducer:
 - (i) electrical input power, chapter 16 and 17.
 - (ii) electromagnetic compatibility, chapter 18 through 21.
 - (iii) explosion, chapter 9.

- DO-160 equipment class D-2 requirements for temperature and altitude, chapter 4.
- DO-160 category B "Severe Humidity" requirements, chapter 6.
- DO-160 "Shock" requirements, chapter 7.
- DO-160 category R "Vibration" requirements, chapter 8.
- DO-160 category W "Waterproofness" requirements, chapter 10.
- DO-160 category H "Hydraulic Fluid" requirements, Chapter 11.
- DO-160 category D "Sand and Dust" requirements, chapter 12.
- DO-160 category F "Fungus Resistance" requirements, chapter 13.
- DO-160 category S "Salt Spray" requirements, chapter 14.

The transducer shall also meet the following functional requirements:

- The transducer shall withstand an aircraft weight range from zero weight to 100% greater than maximum taxi gross weight, without damage or loss of calibration.
- The transducer shall withstand center of gravity range 100% greater than aircraft ground operating CG range without damage or loss of calibration.

3.7 CYCLIC LOADING

The transducers shall withstand, without damage or fatigue, the stresses and deflections of the landing gear during landing, taxi, braking and loading operations for a period equal to 15,000 landing cycles. Maximum loading shall be 300% of aircraft maximum taxi gross weight.

3.8 MAINTAINABILITY AND RELIABILITY

3.8.1 Construction

Standard parts, fittings and fasteners will be used wherever possible.

3.8.2 Component Replacement

A minimum of special tools shall be required to remove and replace transducer and cables. Their replacement shall require a minimum displacement of other aircraft systems and components. It shall be a design objective to be able to replace a transducer or cable, adjust as required, and test within one hour. Transducer and transducer mounting design shall minimize the possibility of transducer damage during removal or replacement.

3.8.3 Calibration

The transducer shall be designed so that calibration shall not be required at intervals of less than that equivalent to 10,000 aircraft flight hours.

3.8.4 Reliability

The transducer shall be designed to have a mean-time between failure not less than that equivalent to 10,000 aircraft flight hours.

3.8.5 Interchangeability

The transducers shall be so designed that they can be replaced by an identical transducer for a particular aircraft type with minimum adjustment of the system and with no requirement for calibration.

APPENDIX A

LIST OF COMPANIES CONTACTED

The following is the list of aircraft operators and manufacturers which were contacted concerning requirements for a weight-sensing transducer for AWABS. The operators can be further classified into three types: (i) major carriers, (ii) commuters, and (iii) cargo service. Those companies which replied to the questionnaires are also noted.

A-1 OPERATORSReplied

MAJOR CARRIERS:

1.	Air Canada	yes
2.	American Airlines	yes
3.	CP Air	yes
4.	Delta Airlines	-
5.	Trans World Airlines	-
6.	United Airlines	yes
7.	Western Airlines	yes

COMMUTER:

8.	Ozark Airlines	-
9.	US Air	yes

CARGO:

10.	Federal Express	yes
11.	Flying Tigers	yes
12.	Seaboard World Airlines	-

<u>MANUFACTURERS</u>	<u>Replied</u>
1. Beech Aircraft Corporation	-
2. Boeing Commercial Airplane Co.	yes
3. Canadair Limited	yes
4. Cessna Aircraft Company	yes
5. DeHavilland Aircraft of Canada Limited	yes
6. Douglas Aircraft Company	yes
7. Fairchild/Swearingen Aviation Corporation	-
8. Gates Learjet	yes
9. Gulfstream American Corporation	yes
10. Lockheed-California Company	yes

APPENDIX B

- B-1 SAMPLE LETTER AND QUESTIONNAIRE TO AN
 OPERATOR.
- B-2 SAMPLE LETTER AND QUESTIONNAIRE TO A
 MANUFACTURER.



DSL Dynamic Sciences Limited

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With the support of Transport Canada's Transportation Development Centre, DSL Dynamic Sciences Limited is developing an onboard aircraft weight and balance system (AWABS) using fiber optic techniques. The system incorporates weight sensing transducers which are installed in the axles of an aircraft's nose and main landing gears, a computer unit which calculates the weight and position of the centre of gravity, controls for operation, and a display unit.

Our system is intended to meet the requirements of Aircraft Recommended Practice (ARP) 1409 issued by the Society of Automotive Engineers for an onboard aircraft weight and balance system. In this ARP we have found requirements which directly influence the design of the weight sensing transducers and these are listed in Attachment 1. Your comments on these aspects of the ARP in terms of your needs for an AWABS would be appreciated.

To ensure that the system will be compatible with your aircraft, we would like to take into account information which is specific to these aircraft. Questions concerning this information are given as part of Attachment 1.

If you can assist us in this matter, we would appreciate an early response. Data which is not immediately available can be sent at a later date, and we shall make every effort to consider it in developing our system. Any comments or questions you may have concerning DSL's AWABS would also be welcome. Thank you for your cooperation.

Yours truly,

DSL DYNAMIC SCIENCES LIMITED

ASPECTS OF ARP 1409

CONCERNING AN AXLE MOUNTED WEIGHT-SENSING TRANSDUCER

The following paragraphs are extracts from ARP 1409 for an onboard aircraft weight and balance system. We would like to have your comments on these paragraphs. Do you feel that they would be acceptable to you as an operator, or would you like them changed, and if so, for what reasons? We would also like your comments to specific questions on your aircraft relating to these paragraphs as given below. If your answers are for a specific aircraft(s), please indicate the aircraft(s) to which you are referring.

Paragraph numbers below correspond to those in the ARP.

4.1.1 Range of Operation: Weights

The system shall determine and display the aircraft weight throughout a range from 10% less than aircraft empty weight to 10% greater than maximum taxi gross weight.

4.1.2 Range of Operation: Centre of Gravity

The system shall determine and display the aircraft centre of gravity throughout a system range determined as follows:

Determine aircraft maximum centre of gravity range expressed in Percent Reference Chord such as Mean Aerodynamic Chord (MAC) or equivalent by subtracting most forward limit from most aft limit. Extend most forward aircraft limit forward by an amount equal to 50% of the aircraft range, but not exceeding the forward point equivalent to zero MAC. Extend most aft aircraft limit aft by an amount equal to 50% of the aircraft range, or to the static aft tipping point, whichever is further aft.

Question: Does such a range of operation for C.G. position seem reasonable to you? If not, why not, and what range would be acceptable to you?

Question: What limits are presently allowed during loading and unloading on the aircraft you operate?

4.3 Accuracy:

The system shall be capable of determining and displaying aircraft weight and centre of gravity within $\pm 1.0\%$ of actual aircraft weight, and $\pm 1.0\%$ Mean Aerodynamic Chord. Lateral centre of gravity if required shall be determined and displayed with 1% of the lateral centre of gravity range.

Question: Are these accuracies on weight and centre of gravity acceptable to you? If not, what are your reasons? What practical limits might you suggest?

4.6 Compatibility:

There shall be no structural, electrical, functioning or servicing interference between the OBWBS (onboard weight and balance system) and any other aircraft system or component, whether the OBWBS is operating, not operating or has experienced any failure mode to be expected in service.

Question: Have you installed any additional hardware around or inside the landing gear axles other than what is supplied by the aircraft manufacturer, which might limit the use of the axle inner bore for the installation of a transducer?

4.7 Environmental and Functional Requirements

4.7.5 The system shall withstand an aircraft weight range from zero weight to 100% greater than maximum taxi gross weight, without damage or loss of calibration.

4.7.6 The system shall withstand centre of gravity range 100% greater than aircraft ground operating c.g. range without damage or loss of calibration.

4.7.7 Cyclic Loading: The sensors shall withstand, without damage or fatigue, the stresses and deflections of the landing gear during loading, taxi, braking and loading operations for a period equal to 15,000 landing cycles. Maximum loading shall be 300% of aircraft maximum taxi gross weight.

Question: How many flight hours does it take to reach 15,000 landing cycles on your aircraft? What is the expected life of your aircraft (in flight hours)?

4.8 Maintainability and Reliability

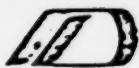
4.8.4 Calibration: The system's components shall be designed so that calibration shall not be required at intervals of less than that equivalent to 10,000 aircraft flight hours.

Question: What is the normal period between overhauls of the aircraft landing gears?

4.8.7 Interchangeability: All components shall be so designed that they can interchange with any identical component for a particular aircraft type with minimum adjustment of the system and with no requirement for calibration.

Question: We feel that the requirement for component interchangeability without recalibration is too severe. Do you concur with this?

Question: Are there not other instruments on your aircraft which require calibration at installation?



DeHavilland Aircraft of Canada Ltd.,
Garratt Boulevard,
Downsview, Ontario
M3K 1Y5

As you may recall, in 1979 DSL Dynamic Sciences Limited investigated the feasibility of using fiber optic techniques for an onboard aircraft weight and balance system (AWABS). With the support of Transport Canada's Transportation Development Centre, DSL is continuing to develop an AWABS using this technology. The system incorporates weight sensing transducers which are installed in the axles of an aircraft's nose and main landing gears, a computer unit which calculates the weight and position of the centre of gravity, controls for operation, and a display unit.

To ensure that the system will be compatible with the commercial aircraft manufactured by DeHavilland, namely: the Twin Otter, Dash-7 and Dash-8, we would like to take into account information which is specific to these aircraft. In general, the information we need relates to the design loads, geometry and environment on the axles of the aircraft. A questionnaire concerning this information is given in Attachment 1. During DSL's previous discussions with DeHavilland, we obtained drawings of the Dash-7 nose and main landing gears and axles. However, data concerning loads, deflections and temperatures on the axles, and aircraft geometry is incomplete, and any further information that you could supply would be appreciated.

Our system is intended to meet the requirements of Aircraft Recommended Practice (ARP) 1409 issued by the Society of Automotive Engineers for an onboard aircraft weight and balance system. In this ARP we have found requirements which directly influence the design of the weight sensing transducers and these are listed in Attachment 2. Your comments on these aspects of the ARP in terms of your needs for an AWABS would be appreciated.

If you can assist us in this matter, we would appreciate an early response. Data which is not immediately available can be sent at a later date, and we shall make every effort to consider it in developing our system. Any comments or questions you may have concerning DSL's AWABS would also be welcome. Thank you for your cooperation.

Yours truly,

DSL DYNAMIC SCIENCES LIMITED

QUESTIONS CONCERNING AIRCRAFT AXLES
AND OPERATING ENVIRONMENT

1. Our transducers are installed to the inner bore of the axles on the nose and main landing gears. Are there constraints which might limit the use of the axle bore, and if so, what proportion of the bore and what locations might remain free for the installation of a transducer? Constraints, for example, might be a tow rod, or anti-skid transducers which are attached to the landing gear axle bores.
2. What are the approximate inner diameters and lengths of the main and nose gear axles? Could you also supply us with a cross-sectional view along the length of the axle?
3. We would like to know how the axle and wheels are attached to the landing gear structure so as to be aware of the load path through the axle. Could you supply us with a drawing or pictorial sketch of the axle and wheel installations? If there are any other devices around the axle which might provide a secondary load path (such as spacer sleeves, disc brakes), could you supply us with a sketch or drawing showing their installations as well?
4. What are the range and typical values of the static vertical loads on each axle?
5. What is the maximum vertical deflection the axle undergoes as a result of the vertical loads? What is the deflection pattern along the axle?
6. What are the maximum design loads on the axles in the longitudinal and lateral directions? For example, these loads might arise due to heavy braking, ground taxiing, or wind loads.
7. Data on aircraft geometry and limits for the centre of gravity location would be desirable. This includes:
 - (i) longitudinal stations of nose and main gear axles.
 - (ii) longitudinal station of leading edge of mean aerodynamic chord (MAC).
 - (iv) length of MAC.
 - (iv) safe loading limits on centre of gravity location for take-off (e.g. in terms of % MAC).

- (v) safe loading limits on centre of gravity location for ground handling (e.g. in terms of % MAC).

8. What are the maximum temperatures likely to be on the axles, for example, as a result of heavy braking?
9. What levels of shock loads (in units of "lbs") and accelerations (in "g"'s) are likely to be experienced by the axle during normal and heavy landings?

ASPECTS OF ARP 1409
CONCERNING THE WEIGHT-SENSING TRANSDUCER

The following paragraphs are extracts from ARP 1409 for an onboard aircraft weight and balance system. We would like to have your comments on these paragraphs. Do you feel that they would be acceptable to you as an aircraft manufacturer, or would like them changed, and if so, for what reasons? We would also like your comments to specific questions relating to a few of these paragraphs as given below. If your answers are for a specific aircraft(s), please indicate the aircraft(s) to which you are referring.

Paragraph numbers below correspond to those in the ARP.

4.1.1 Range of Operation: Weights

The system shall determine and display the aircraft weight throughout a range from 10% less than aircraft empty weight to 10% greater than maximum taxi gross weight.

4.1.2 Range of Operation: Centre of Gravity

The system shall determine and display the aircraft centre of gravity throughout a system range determined as follows:

Determine aircraft maximum centre of gravity range expressed in Percent Reference Chord such as Mean Aerodynamic Chord (MAC) or equivalent by subtracting most forward limit from most aft limit. Extend most forward aircraft limit forward by an amount equal to 50% of the aircraft range, but not exceeding the forward point equivalent to zero MAC. Extend most aft aircraft limit aft by an amount equal to 50% of the aircraft range, or to the static aft tipping point, whichever is further aft.

Question: Does such a range of operation for C.G. position seem reasonable to you? If not, why not, and what range would be acceptable to you?

4.3 Accuracy:

The system shall be capable of determining and displaying aircraft weight and centre of gravity

within $\pm 1.0\%$ of actual aircraft weight and $\pm 1.0\%$ Mean Aerodynamic Chord. Lateral centre of gravity if required shall be determined and displayed with 1% of the lateral centre of gravity range.

Question: Are these accuracies on weight and centre of gravity acceptable to you? If not, what are your reasons? What practical limits might you suggest?

4.7 Environmental and Functional Requirements

4.7.5 The system shall withstand an aircraft weight range from zero weight to 100% greater than maximum taxi gross weight, without damage or loss of calibration.

4.7.6 The system shall withstand centre of gravity range 100% greater than aircraft ground operating c.g. range without damage or loss of calibration.

4.7.7 Cyclic Loading: The sensors shall withstand, without damage or fatigue, the stresses and deflections of the landing gear during landing, taxi, braking and loading operations for a period equal to 15,000 landing cycles. Maximum loading shall be 300% of aircraft maximum taxi gross weight.

4.8 Maintainability and Reliability

4.8.4 Calibration: The system's components shall be designed so that calibration shall not be required at intervals of less than that equivalent to 10,000 aircraft flight hours.

4.8.7 Interchangeability: All components shall be so designed that they can interchange with any identical component for a particular aircraft type with minimum adjustment of the system and with no requirement for calibration.

APPENDIX C

SPECIFIC REQUIREMENTS FOR A WEIGHT-
SENSING TRANSDUCER FOR AN ON-BOARD
AIRCRAFT WEIGHT AND BALANCE SYSTEM



SPECIFIC REQUIREMENTS FOR
A WEIGHT-SENSING TRANSDUCER
FOR AN ONBOARD AIRCRAFT WEIGHT
AND BALANCE SYSTEM

Interim Information Report
prepared for
Transport Canada
Transportation Development Centre

Contract file 09SD.T8200-0-0543
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DSL Dynamic Sciences Limited
St-Laurent, Que.

Report C162-2, Rev. 1
January, 1983

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1.0 INTRODUCTION

As part of the project to develop a fiber optic weight sensor for an onboard aircraft weight and balance system (AWABS), DSL Dynamic Sciences Limited defined a list of general requirements for an AWABS transducer, which is given in DSL report C162-01 [1]. These requirements are applicable to any commercial aircraft.

In this report, specific requirements and engineering parameters are defined for AWABS transducers for the nose and main landing gears of a 40,000 lbs maximum weight aircraft similar to the Canadair CL-600 Challenger. This aircraft was chosen to be the case study for the project. The requirements in this report do not replace, but rather, complement those given in report C162-01. Both reports are concerned solely with requirements which influence the weight-sensing transducers and the transmission components to and from the transducers, and not with requirements for the total AWABS.

The report is based on the best information presently available to DSL, as gathered through discussions between Canadair and DSL personnel, and through other sources. The data will be subject to revision and updating as the project continues.

The report provides both the parameter values for design of the transducers, and the information from which the values were derived.

2.0 REQUIREMENTS

This chapter contains parameter values which are needed for the design of AWABS transducers for a 40,000 lbs maximum weight aircraft similar to the Canadair CL-600 Challenger.

Section 2.1 below defines the levels of accuracy for the transducers and the range of loads and operating conditions under which the given levels of accuracy are to be maintained. Section 2.2 defines conditions under which the transducers must maintain their functional integrity, both with and without possible loss of calibration. Environmental requirements are also covered. Section 2.3 defines compatibility requirements of the transducers with the aircraft, and section 2.4 covers other requirements.

As it has been assumed that there is a separate transducer for each wheel, the values given below (for example, range of vertical load), are for one wheel, or one transducer.

2.1 ACCURACY REQUIREMENTS

The following paragraphs provide levels of accuracy required of the transducers and conditions under which the specified accuracy must be maintained.

2.1.1 Levels of Accuracy

Nose gear: minimum absolute accuracy = ± 15 lbs
 : percentage accuracy = $\pm 1.10\%$ of actual load

Main gear: minimum absolute accuracy = ± 37 lbs
 : percentage accuracy = $\pm \left[\begin{array}{l} 1.0\% \text{ of actual load} \\ \text{less } 7.5 \text{ lbs.} \end{array} \right]$

These accuracies were derived from a trade-off study of transducer accuracy requirements to meet the system accuracy criteria of $\pm 1\%$ weight and $\pm 1\%$ MAC given in ARP 1409 [2], as they apply to the Challenger aircraft. The data on aircraft weight and geometry used in the trade-off study and for other sections of this report are given in Appendix A and details of the trade-off study are given in Appendix B. The minimum absolute accuracies given above correspond to the aircraft condition of manufacturer's weight empty (MWE) less 10%.

2.1.2 Range of Vertical Loads

The following are the normal vertical loads for each transducer.

Nose gear: minimum load = 0 (lbs)
 : maximum load = 3500 (lbs)

Main gear: minimum load = 3700 (lbs)
 : maximum load = 11000 (lbs)

The normal vertical load is defined as the static load condition while the aircraft is on level ground. The minimum nose gear transducer load corresponds to static aft tipping of the aircraft; the maximum nose gear load, to maximum ramp weight (MRW) plus 10% MRW, with the centre of gravity (CG) at the most forward limit of 5% of Mean Aerodynamic Chord (MAC). The minimum main gear transducer load corresponds to manufacturer's weight empty (MWE) less 10% with CG at 5% MAC; maximum load to static aft tipping at MRW plus 10%. These are limits based on ARP 1409, and were derived from the aircraft data given in Appendix A.

2.1.3 Other Loads

The transducers must maintain the stated levels of accuracy given in 2.1.1 over the range of vertical loads given in 2.1.2 in the presence of other types of axle loads having the following ranges (per transducer).

Longitudinal Load = $\pm$ 5500 (lbs) ... main gear
 = $\pm$ 350 (lbs) ... nose gear

Lateral Load = $\pm$ 1100 (lbs) ... main gear
 = $\pm$ 350 (lbs).... nose gear

Torsion Loads = $\pm$ 100 (lb-in) ... main gear
 = $\pm$ 100 (lb-in) ... nose gear

The maximum longitudinal load on the main gear is based on a fully braked wheel using a coefficient of adhesion between the aircraft tire and runway surface of 0.5. The given lateral loads for both gears and the nose gear longitudinal load correspond to lateral and longitudinal ramps having a maximum slope of 6°. There are no torsion loads on the nose gear axle because it is not equipped with brakes. Torsion loads do not occur on the main gear axle since the load path for the brakes is not through the axle.¹ The given values ensure that the design not be sensitive to torsion.

2.1.4 Temperature Conditions

The transducers must maintain the stated levels of accuracy under the following temperature conditions.

1. It is possible that the brake disc and caliper carry some vertical load during braking. Depending on the extent of this effect, accurate readings from an axle-mounted weight sensor may require releasing of the brakes.

temperature ranges: - 60°C to + 225°C main gear
: - 60°C to + 50°C nose gear

The minimum temperatures correspond to the aircraft at an altitude of 40,000 feet. The maximum temperature on the main gear is a result of a high-energy stop (for example, a rejected take-off), while for the nose gear, it corresponds to the aircraft on a hot airstrip.

2.1.5 Humidity Requirements

The aircraft may be subjected to extremes of from 0% to 100% relative humidity at temperatures from -60°C to +50°C due to various climatic conditions on airstrips. The transducers must maintain the stated levels of accuracy under these conditions.

2.2 SYSTEM INTEGRITY

Environmental and load conditions on the transducers can exceed the ranges defined in paragraph 2.1. Although the transducers need not maintain the stated levels of accuracy outside the conditions of 2.1, they must survive under the conditions defined below.

2.2.1 Environmental Requirements

The transducers shall meet the following requirements for environmental conditions and test procedures of Radio Technical Commission for Aeronautics Document No. DO-160 [3].

- : Temperature and Altitude Requirement for Equipment, chapter 4 class D-2.
- : Severe Humidity Requirements, chapter 6 category B.
- : Shock Requirements, chapter 7.
- : Vibration Requirements, chapter 8, category R.
- : Waterproofness Requirement, chapter 10, category W.
- : Hydraulic Fluid Requirement, chapter 11, category H.
- : Sand and Dust Requirement, chapter 12, category D.
- : Fungus Resistance Requirement, chapter 13, category F.
- : Salt Spray Requirement, chapter 14, category S.

These requirements specify a "laboratory means of determining the performance characteristics" of the transducer "under conditions representative of those which may be encountered in actual aeronautical operations".

2.2.2 Without Loss of Calibration

The transducers shall withstand without damage or loss of calibration the following range of loads:

Nose gear: zero to 7000 lbs

Main gear: zero to 22000 lbs

The maximum values of loads are in accordance with the ARP 1409 requirement for withstanding 100% greater load than maximum taxi gross weight.

These load ranges cover the normal range of conditions encountered during taxi, braking, loading operations, and severe landing.

2.2.3 With Possible Loss of Calibration

A range of operating conditions more severe than those defined under 2.2.2 may occur. In such cases, the transducers shall withstand, without damage or fatigue, the loads given below for a period equal to 15,000 landing cycles. Based on the ARP 1409 criterion for withstanding 300% maximum taxi gross weight, the maximum loads are:

Nose gear 10500 lbs.

Main gear 33000 lbs.

These loads are more severe than load estimates provided by Canadair: a typical peak load is 30,000 lbs per main gear axle (or, assuming equal distribution, 15,000 lbs per transducer) as a result of a heavy landing.

The time interval to develop these maximum loads is approximately 50 milliseconds. Assuming a linear increase of force versus time, the maximum rates of loading are:

Nose gear 2.10×10^5 lbs/second

Main gear 6.60×10^5 lbs/second.

2.3 COMPATIBILITY

The transducers shall meet the geometric size limitations imposed by the geometry of the landing gear axles as given below:

	NOSE GEAR	MAIN GEAR
Axle Inner Diameter (at end of axle)	1.15 in.	1.70 in.
Axle Inner Diameter (between axle support and inboard bearing)	1.10 in.	2.10 in.
Available Length of Inner Diameter (from centreline of axle to install transducer)	8.7 in.	6.5 in.

The main gear transducer shall neither interfere with the anti-skid transducer mounted to the end of the axle, nor with the anti-skid cabling in the axle.

The mounting of the transducers shall not require structural modifications to the axles.

2.4 OTHER REQUIREMENTS

The transducers shall meet the requirements for items as given in paragraphs 3.4 and 3.8 of DSL report C162-01 [1]. These items concern transducer weight and the following maintainability and reliability aspects:

- : Construction
- : Component Replacement
- : Calibration
- : Reliability
- : Interchangeability

REFERENCES

1. DSL Dynamic Sciences Limited:
Report Cl62-01 "General Requirements for a Weight-Sensing Transducer for an Onboard Aircraft Weight and Balance System", March 1982.
2. Society of Automotive Engineers:
Aerospace Recommended Practice ARP 1409 for "Requirements for Aircraft Onboard Weight and Balance System", January 1978.
3. Radio Technical Commission for Aeronautics (RTCA):
Document DO-160 "Environmental Conditions and Test Procedures for Airborne Electronic/Electrical Equipment and Instruments", 28th February 1975.

APPENDIX AWEIGHT AND BALANCE DATA FOR CANADAIR CHALLENGER1. Weights

: Manufacturer's Weight Empty	(MWE)	20000	lbs
: Maximum Ramp Weight	(MRW)	40000	lbs

2. Centre of Gravity (CG) Limits

: Forward CG limit	(all weights)	15% MAC
: Aft CG limit	(all weights)	35% MAC

3. Mean Aerodynamic Chord (MAC)

: Length of MAC	92.64	in
: Position of leading edge of MAC (0% MAC)	STA 488.025	(fuselage station)

4. Landing Gear

: Wheelbase	26 ft	2.5 in
: Track	10 ft	5 in
: Nose Track		11.5 in
: Position of Nose Gear Axle	fuselage STA 226.00	
: Position of Main Gear Axle (fully compressed)	fuselage STA 542.75	

APPENDIX BSTUDY OF ACCURACY REQUIREMENTS FOR
AWABS TRANSDUCERS

A study was made of the accuracy requirements for weight sensing transducers at the nose and main gears of the Canadair CL-600 Challenger aircraft. The values of the required accuracy of the transducers were established so as to meet the SAE specification ARP 1409 on system accuracy of $\pm 1\%$ actual aircraft weight and $\pm 1\%$ Mean Aerodynamic Chord (MAC).

The study showed that there is a trade-off between the accuracies of the two nose gear transducers and the four main gear transducers; that is, a higher accuracy on the main gear transducers would allow a lower accuracy on those of the nose gear, and vice versa. Figure C-1 shows this accuracy trade-off in terms of allowable percentage error for each transducer. The position on where we should lie on the trade-off curve was selected to maximize the product of the nose gear error and the main gear error, and is indicated in Figure C-1 by " Δ ". At this position we obtain the following requirements.

NOSE GEAR TRANSDUCER

: allowable percentage error $\pm 1.22\%$ of actual load

MAIN GEAR TRANSDUCERS

: allowable percentage error $\pm 0.95\%$ of actual load

At low levels of loads, it becomes impractical for a transducer to maintain its stated allowable percentage error and some minimum value of error is often used. As a result, the allowable errors for the transducers were re-examined to include this characteristic, and the following accuracy requirements were established.

NOSE GEAR TRANSDUCER

: allowable percentage error $\pm 1.1\%$ of actual load
 : minimum absolute error ± 15 lbs.

MAIN GEAR TRANSDUCER

: allowable percentage error $\pm \left[\begin{array}{l} (1.0\% \text{ of actual load}) \\ \text{less } (7.5 \text{ lbs}) \end{array} \right]$
 : minimum absolute error ± 37 lbs.

The minimum absolute error is defined as the lowest permissible error (in units of lbs), the transducer must maintain over its range of operation. Allowable percentage error is defined as the allowable error in terms of the actual load to be measured. The percentage error applies over the range of operation down to the limit at which the minimum absolute error is reached. The error limits are best understood when plotted as a function of actual load and are shown in Figures C-2 and C-3 for the nose and main gear transducers respectively.

The study concluded with an analysis of the overall system errors using the above allowable errors for six aircraft load conditions. These conditions were:

1. Maximum Weight / Aft-most CG
2. Maximum Weight / Nominal CG
3. Maximum Weight / Fore-most CG
4. Minimum Weight / Aft-most CG
5. Minimum Weight / Nominal CG
6. Minimum Weight / Fore-most CG

where: Maximum weight = 44000 lb
 Minimum weight = 18000 lb
 Aft-most CG = 55% MAC or 4.05" from main gear
 Nominal CG = 25% MAC or 31.57" from main gear
 Fore-most CG = 5% MAC or 50.40" from main gear

For each of the above aircraft load conditions, two sets of transducer errors were used: the first gave the worst possible error on weight; the second, the worst possible error on CG position. The computed worst-case system errors were then compared to the ARP accuracy requirements. The analysis showed that the accuracy requirements of $\pm 1\%$ actual weight and $\pm 1\%$ MAC were always met and often surpassed.

As a result, it was concluded that the specification of individual transducer accuracies can be used as a means of specifying overall system accuracy requirements. The individual accuracy limits can then provide a criterion for the design of a particular transducer.

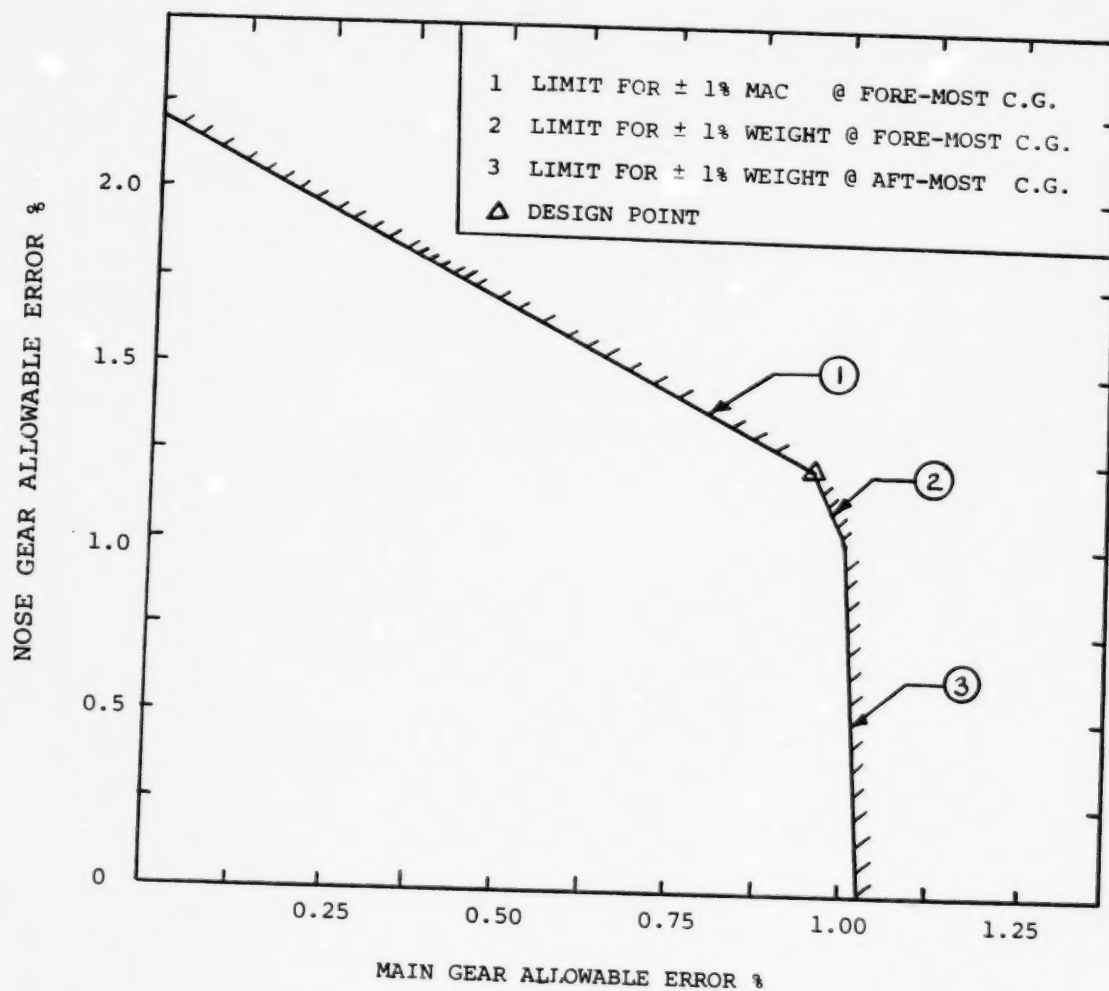


FIGURE C-1 PERCENTAGE ERROR TRADE-OFF
BETWEEN NOSE AND MAIN GEAR TRANSDUCERS

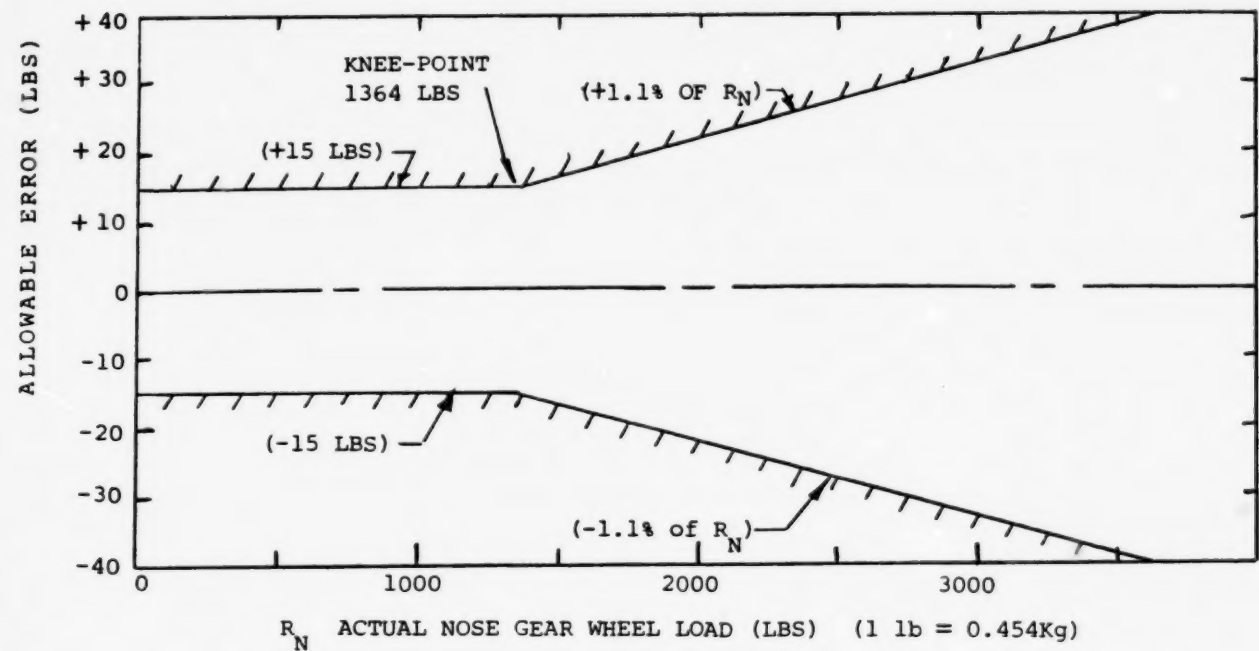


FIGURE C-2 ALLOWABLE TRANSDUCER ERROR VERSUS WHEEL LOAD
- CHALLENGER NOSE GEAR

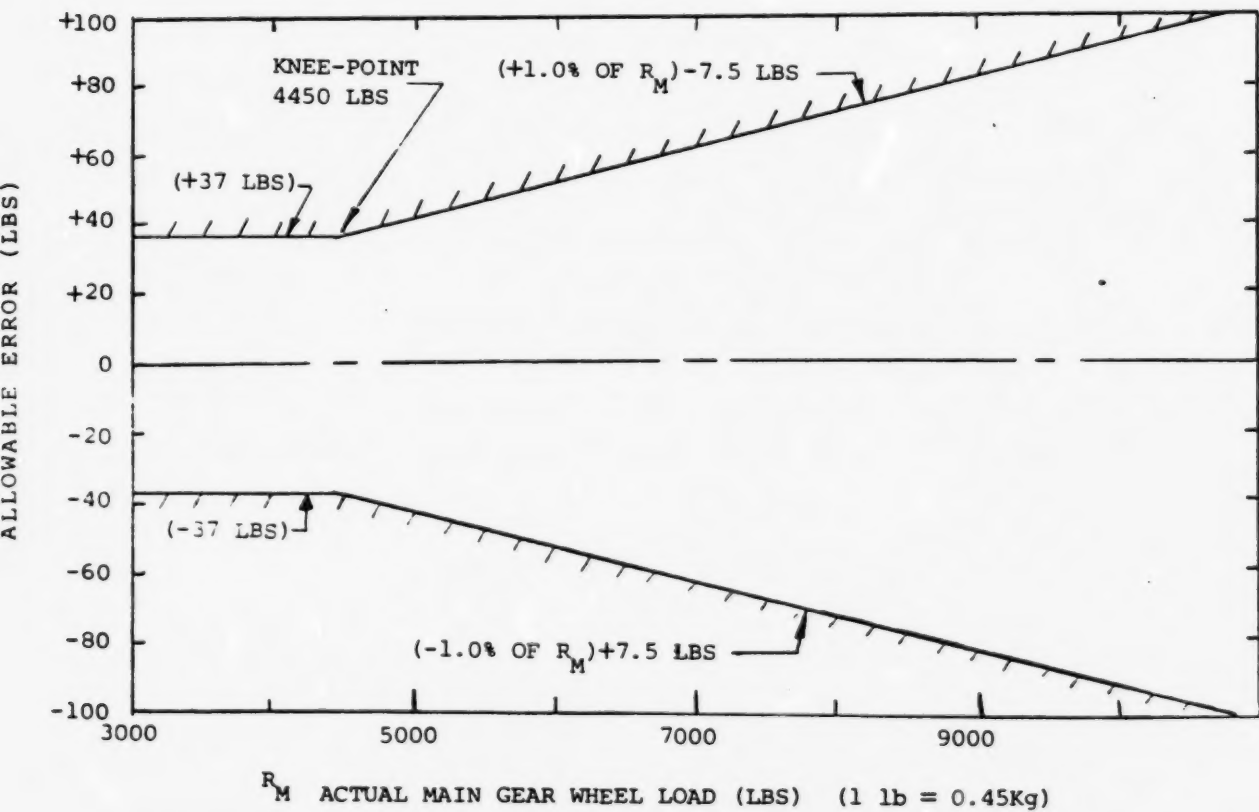


FIGURE C-3 ALLOWABLE TRANSDUCER ERROR VERSUS WHEEL LOAD
- CHALLENGER MAIN GEAR

EQUATIONS FOR ALLOWABLE ERROR ANALYSIS

The equation for absolute error for CG position is:

$$\epsilon_N \left[1 - \left(\frac{\epsilon_d}{l} + \frac{R_N}{W} \right) \right] + 2\epsilon_M \left(\frac{\epsilon_d}{l} + \frac{R_N}{W} \right) = W \left(\frac{\epsilon_d}{l} \right) \quad \dots (1)$$

The equation for absolute error for weight is:

$$\epsilon_N + 2\epsilon_M = \epsilon_W \quad \dots (2)$$

The equation for percentage error for CG position is:

$$\xi_N \left(\frac{R_N}{W} \right) \left[1 - \left(\frac{\epsilon_d}{l} + \frac{R_N}{W} \right) \right] + 2\xi_M \left(1 - \frac{R_N}{W} \right) \left(\frac{\epsilon_d}{l} + \frac{R_N}{W} \right) = \frac{\epsilon_d}{l} \quad \dots (3)$$

The equation for percentage error for weight is:

$$\xi_N \left(\frac{R_N}{W} \right) + 2\xi_M \left(1 - \frac{R_N}{W} \right) = \xi_W \quad \dots (4)$$

where: ϵ_N = absolute error on nose gear (lb)

ϵ_M = absolute error on main gear (lb)

ϵ_d = allowable absolute error on CG position (in)

ϵ_W = allowable absolute error on weight (lb)

ξ_N = percentage error on nose gear

ξ_M = percentage error on main gear

ξ_W = allowable percentage error on weight (lb)

and: R_N = actual nose gear load (lb)

W = actual weight of aircraft (lb)

l = aircraft wheelbase between nose
and main gears (in)

APPENDIX D

TEST RESULTS



TEST RESULTS

This appendix contains results from the tests performed on the optical transducer system. The results are divided into five groups as follows:

<u>Group</u>	<u>Description</u>	<u>Figures</u>
I	Load Tests on Transducer Alone	D-1 to D-5
II	Load Tests on Transducer Installed in the Axle Tube	D-6 to D-10
III	Temperature Tests on Transducer Alone	D-11, D-12
IV	Electrical Strain Gauge Results	D-13, D-14
V	Comparisons between Test and Theory	Tables D-1, D-2

Descriptions of the formats of these results are provided below:

GROUPS I and II

For these tests, the output from the fringe counter has been plotted against the applied load (in units of Newtons) as measured by the load cell built into the loading block (for vertical loads), or as determined by the deflection of the tensioning springs (for each non-vertical load). Results from the three load/unload cycles of each test are shown.

Because the sensitivity of the transducer to vertical load is high, it is difficult to interpret any variance in the test data using the graph of fringe count versus vertical load. As a result, the data were replotted in terms of the deviation of the measured fringe count from an estimated best

linear fit through the data. These graphs, shown in Figures D-2 and D-7, basically display the repeatability of the sensor by removing its sensitivity to the vertical load. The same scaling has been used for the fringe count deviation as for the non-vertical load results, allowing direct comparisons of all load test results.

GROUP III

The graphs in this group show fringe counter output versus the ambient temperature measured in the temperature chamber at a location close to the sensor tube. In these tests, differing lengths of the two input fibres were exposed to the temperature changes, and are denoted configurations T1, T2 and T3. Configuration T1 was the base case; the exposed length of one of the fibres was 22mm longer and 23 shorter than for T1 in configurations T2 and T3 respectively.

GROUP IV

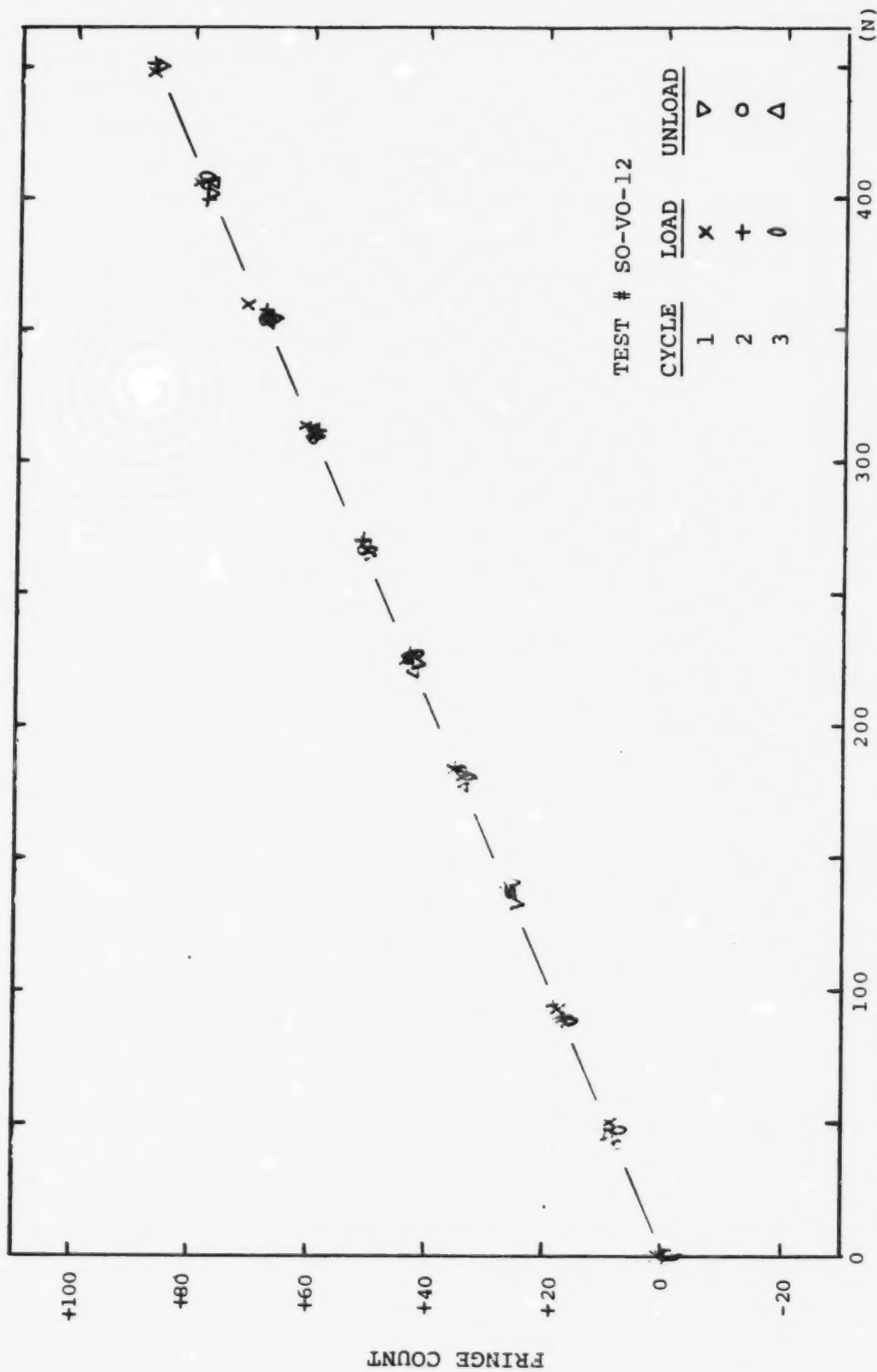
These graphs show the output from the shear and bending electrical strain gauges mounted on the sensor tube for a typical vertical load, sensor only test.

GROUP V

In these tables, comparisons are made between the experimental values of fringe count, bending and shear strains and those predicted from the finite element analyses. The experimental values are the mean values derived from the test results. Where the sign "=" is shown, it indicates that due to the presence of drift and scatter, this value has been approximated.

The left hand column of each table indicates the load condition, magnitude of the load and its moment arm, and the test number from which the experimental values were obtained.

For ease of comparison, the ratios of experimental to theoretical values are also given except for the cases of longitudinal and torsional loads, where the theoretical values are zero.



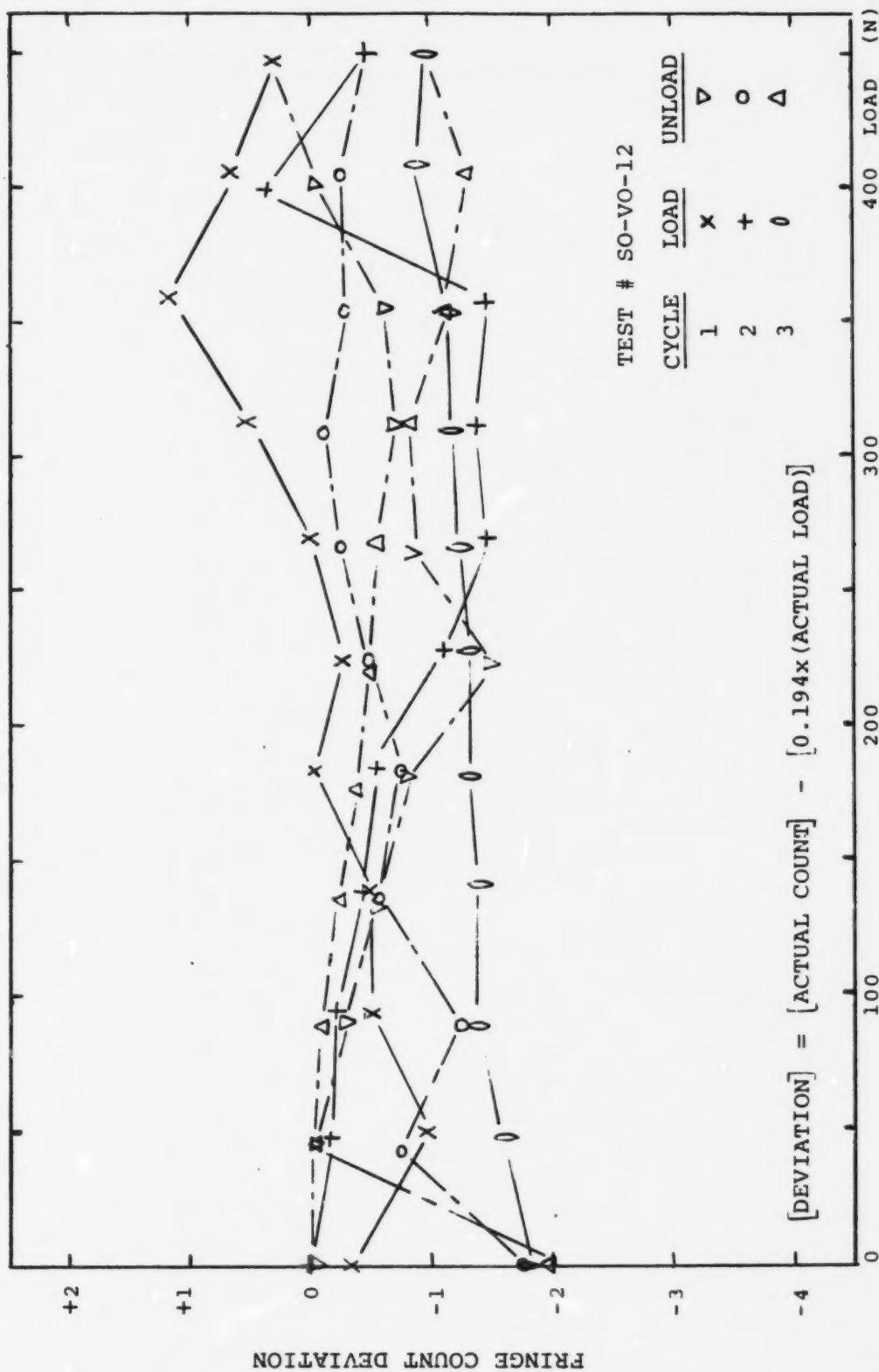


FIGURE D-2 OPTICAL TRANSDUCER DEVIATION VERSUS VERTICAL LOAD
- SENSOR ONLY CONFIGURATION

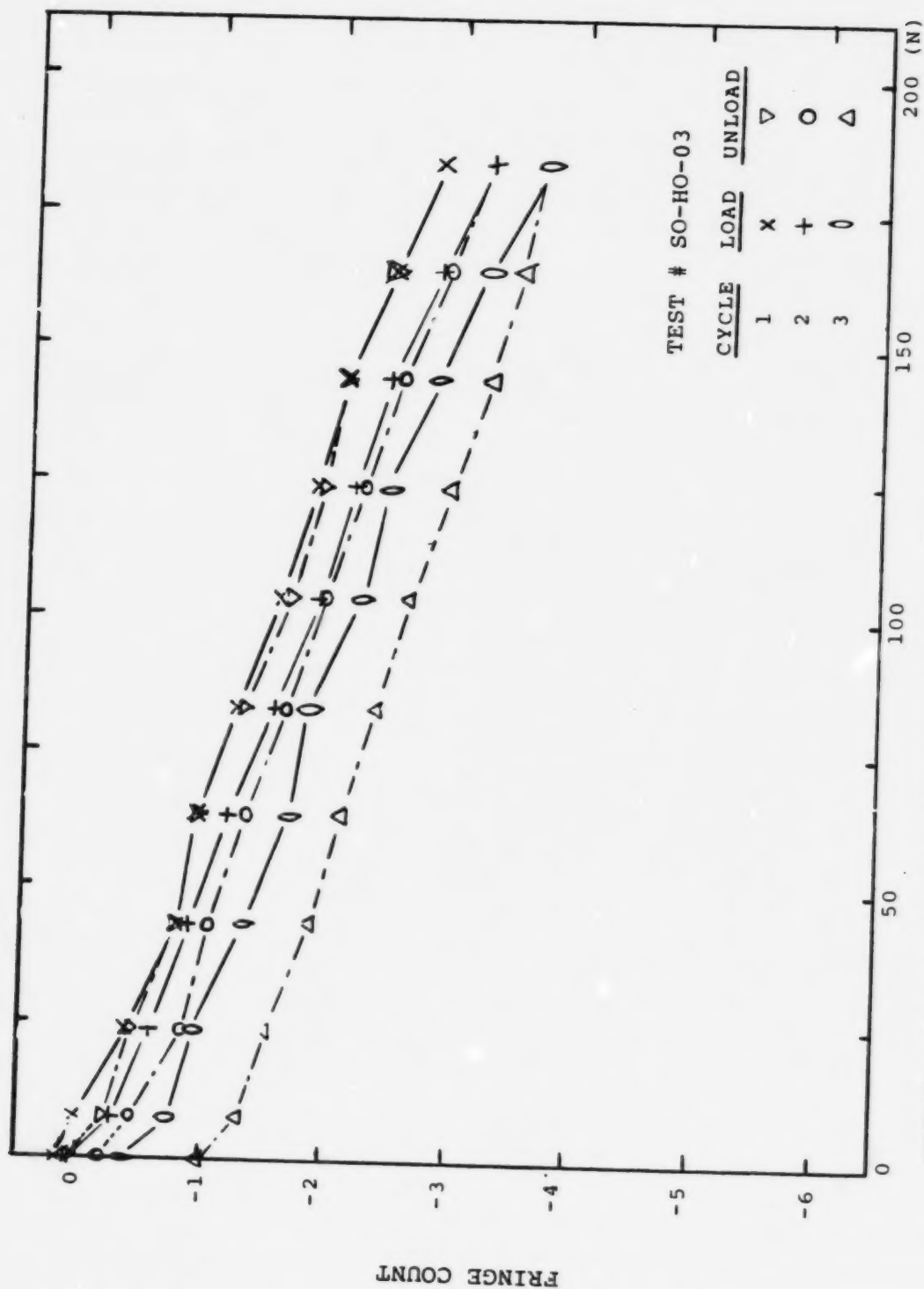


FIGURE D-3 OPTICAL TRANSDUCER OUTPUT VERSUS LATERAL LOAD
- SENSOR ONLY CONFIGURATION

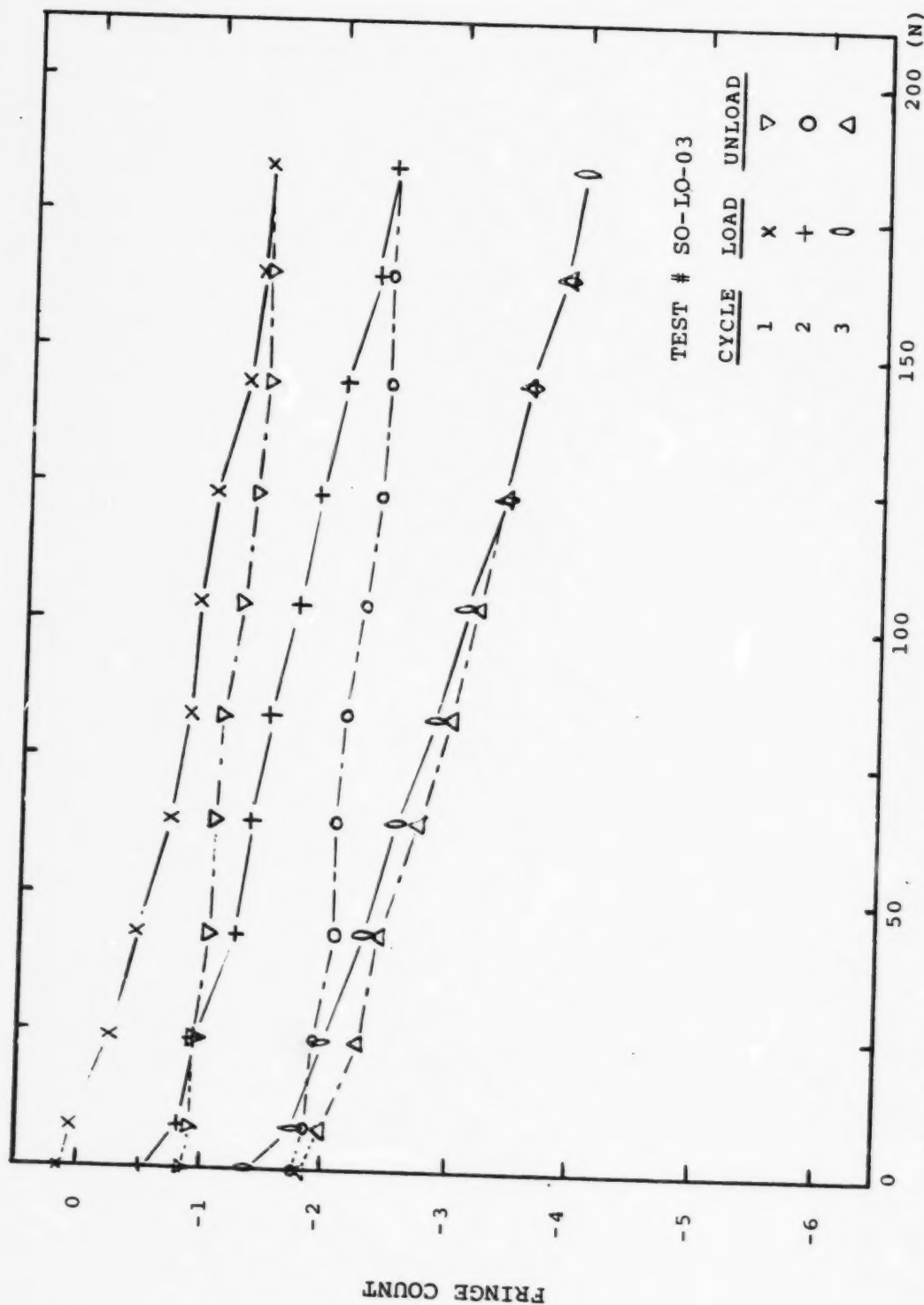
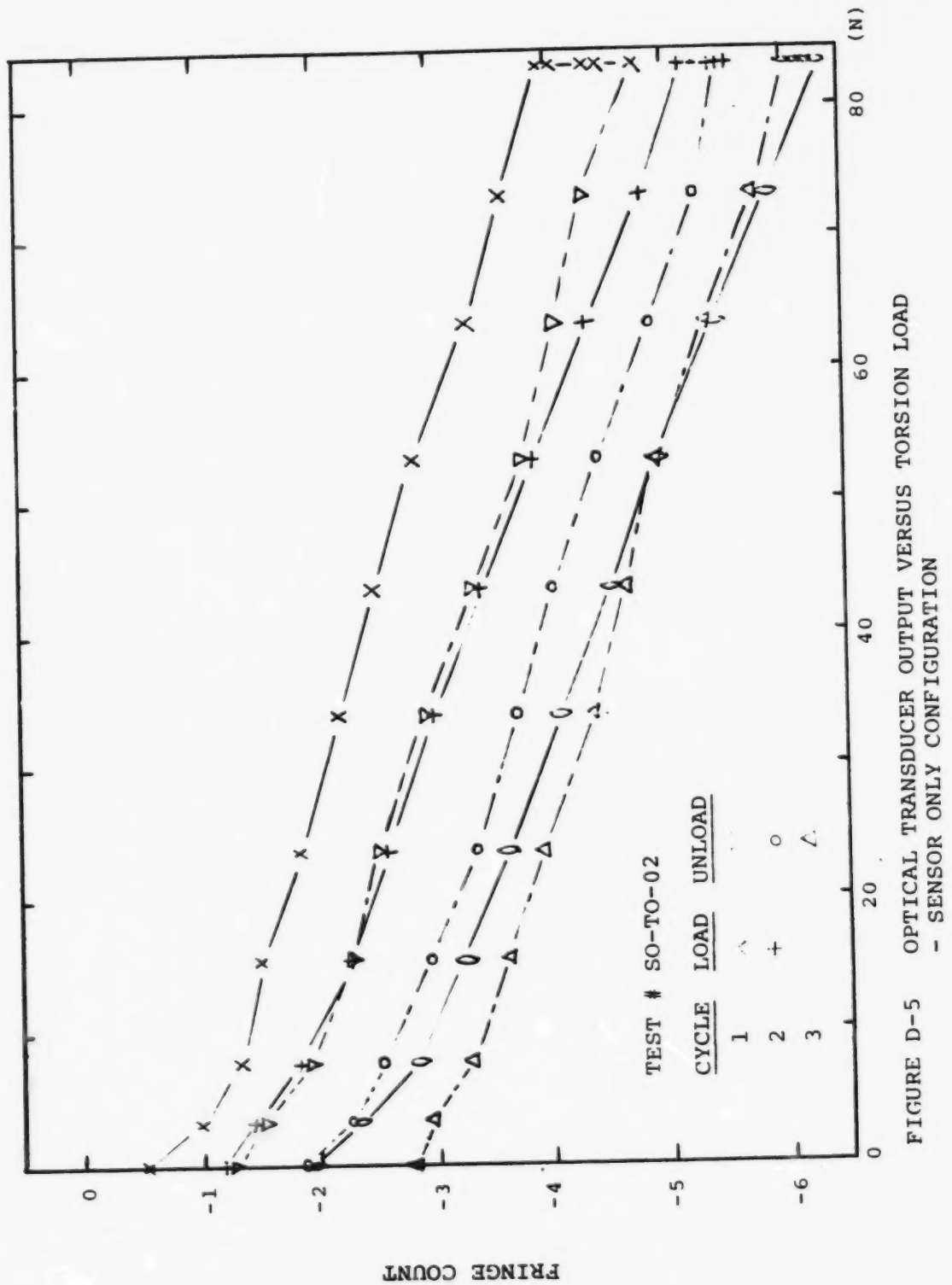


FIGURE D-4 OPTICAL TRANSDUCER OUTPUT VERSUS LONGITUDINAL LOAD
- SENSOR ONLY CONFIGURATION



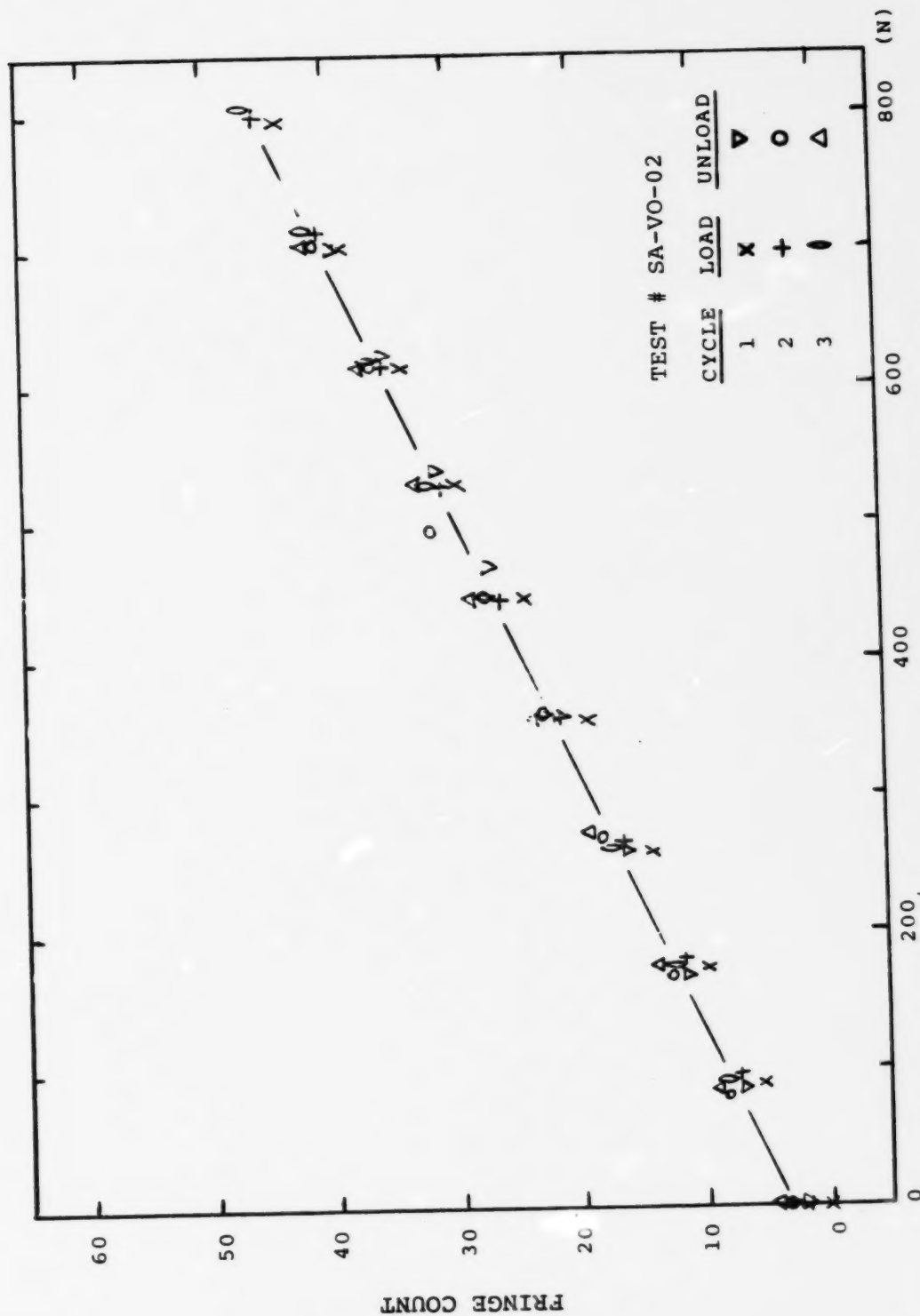


FIGURE D-6 OPTICAL TRANSDUCER OUTPUT VERSUS VERTICAL LOAD
- SENSOR AND AXLE CONFIGURATION

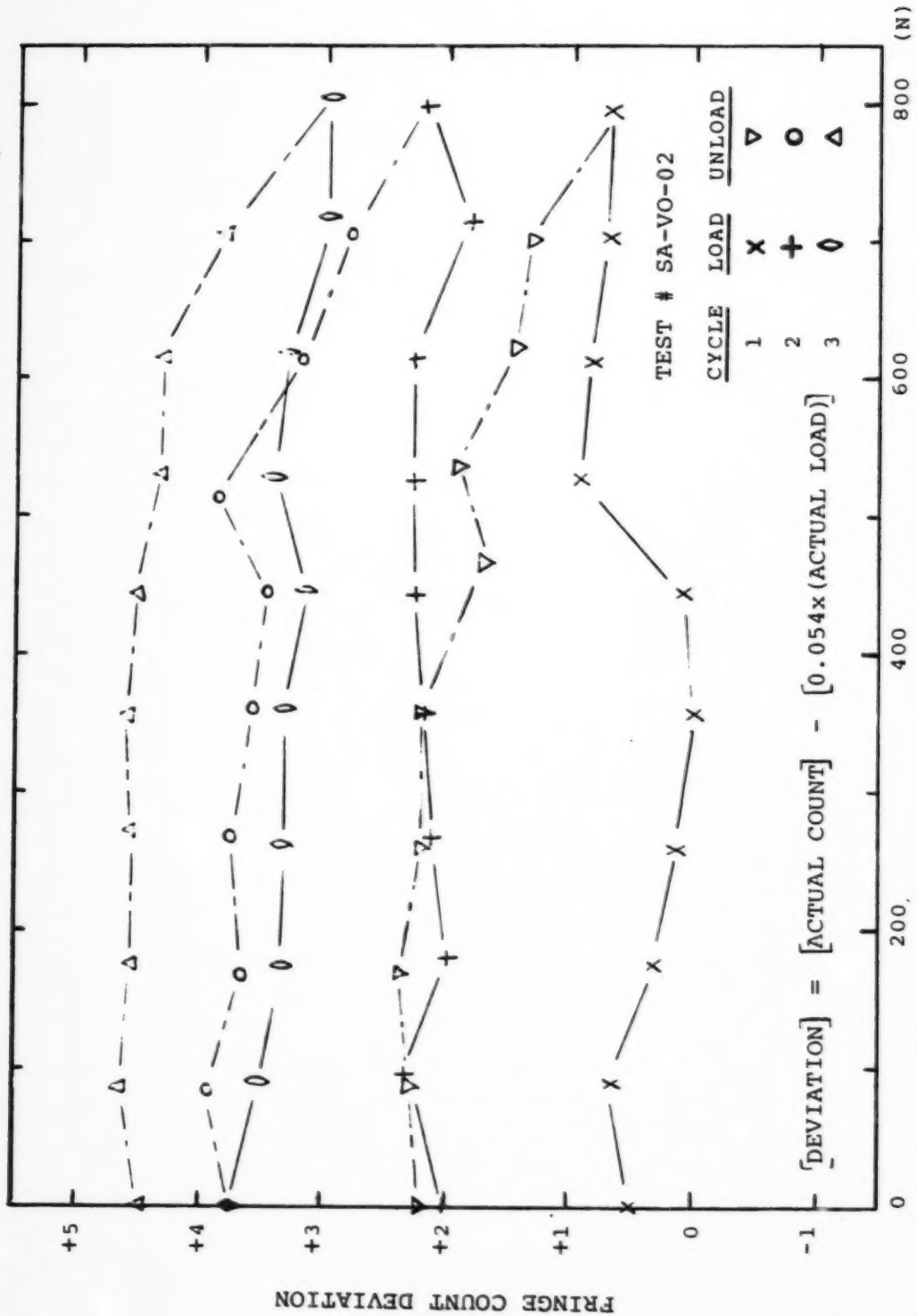
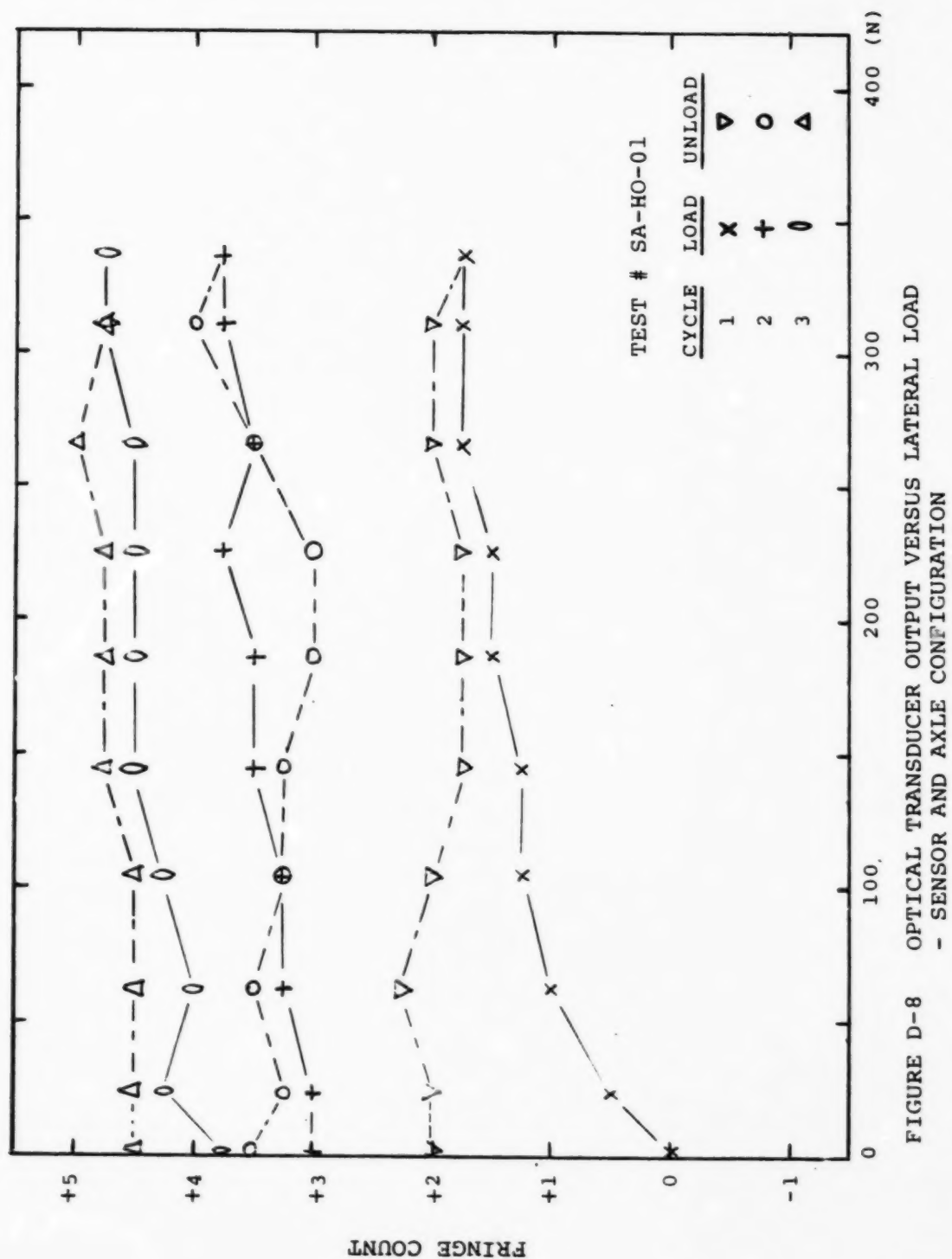


FIGURE D-7 OPTICAL TRANSDUCER DEVIATION VERSUS VERTICAL LOAD
- SENSOR AND AXLE CONFIGURATION



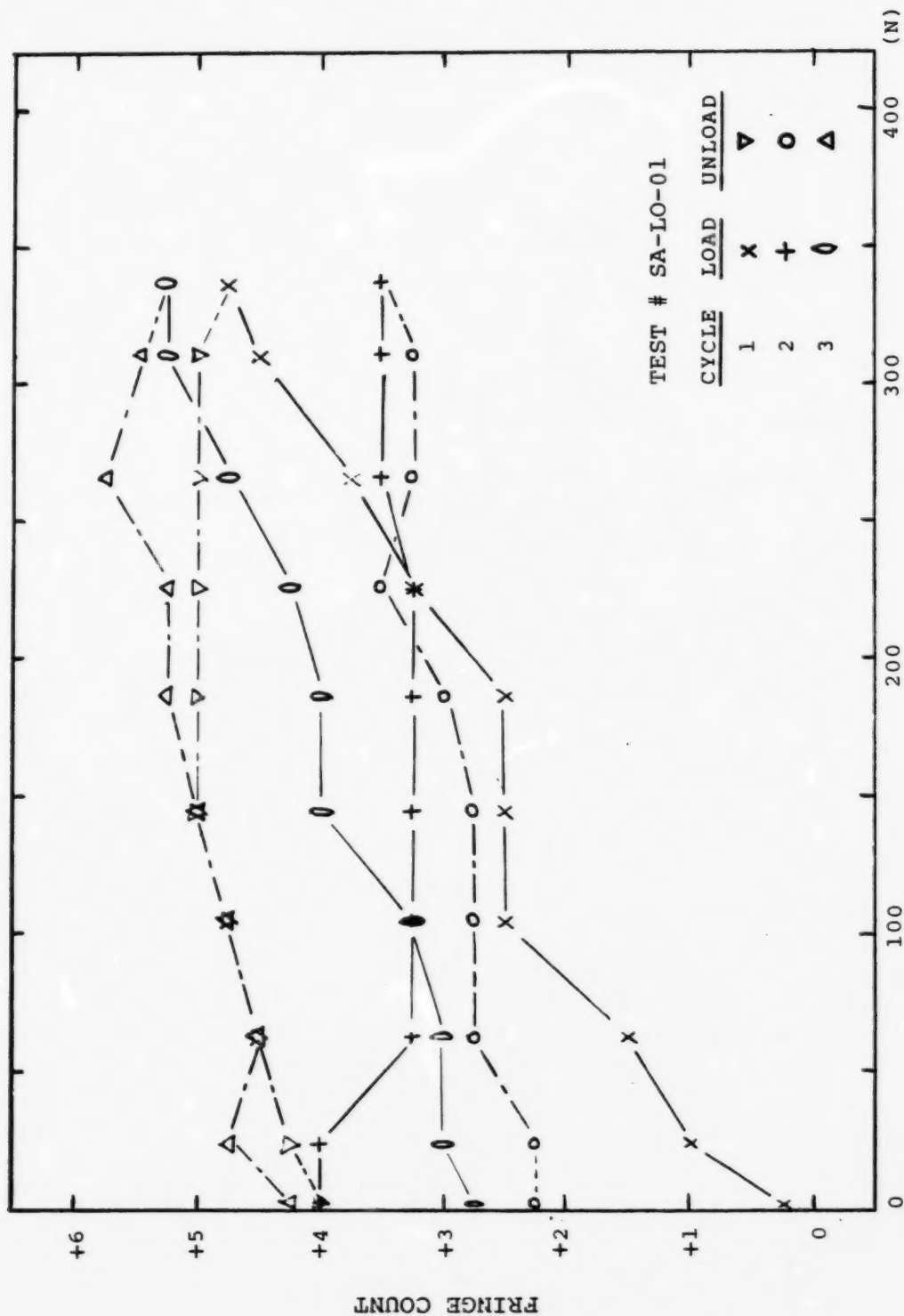


FIGURE D-9 OPTICAL TRANSDUCER OUTPUT VERSUS LONGITUDINAL LOAD
- SENSOR AND AXLE CONFIGURATION

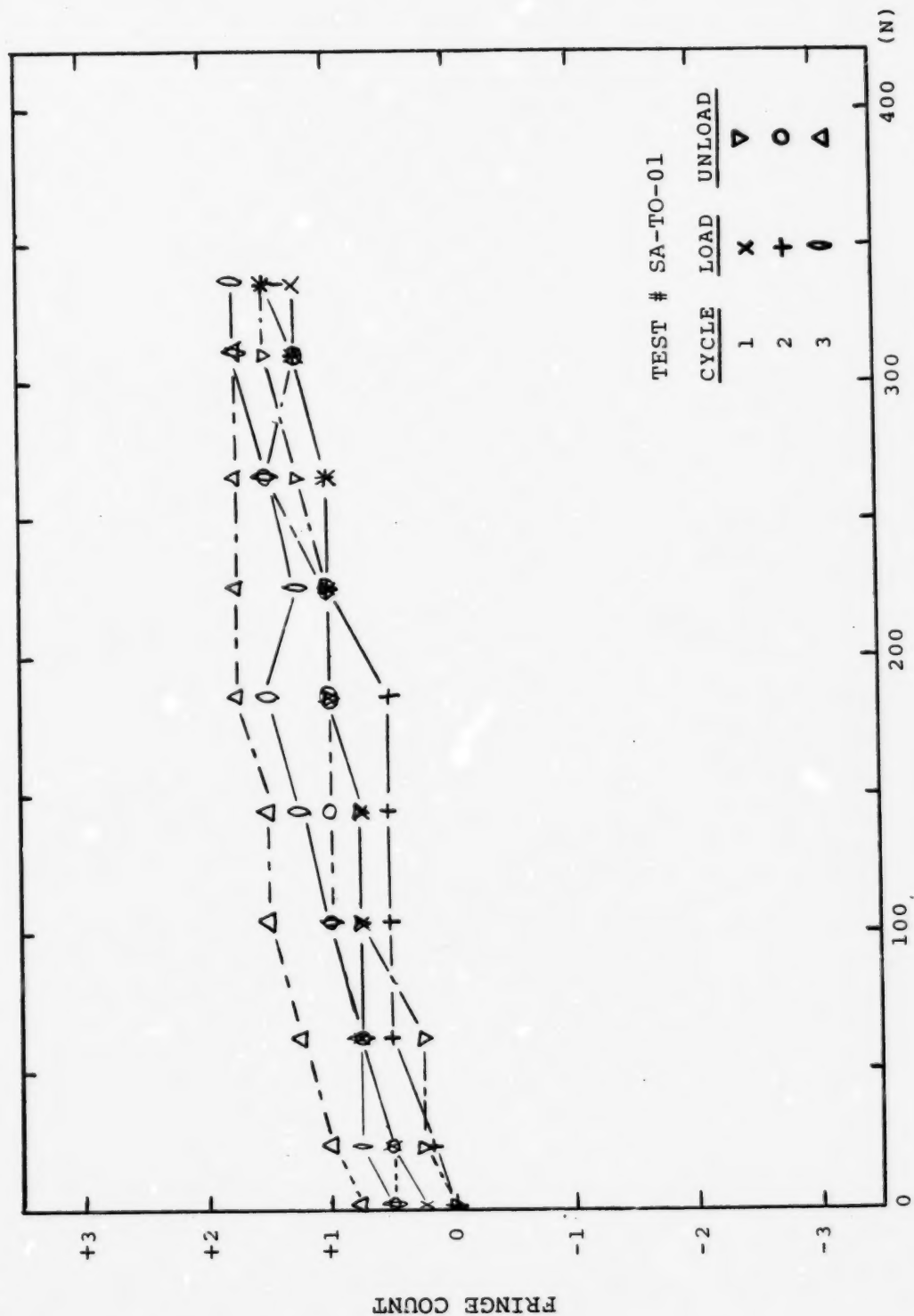


FIGURE D-10 OPTICAL TRANSDUCER OUTPUT VERSUS TORSION LOAD
- SENSOR AND AXLE CONFIGURATION

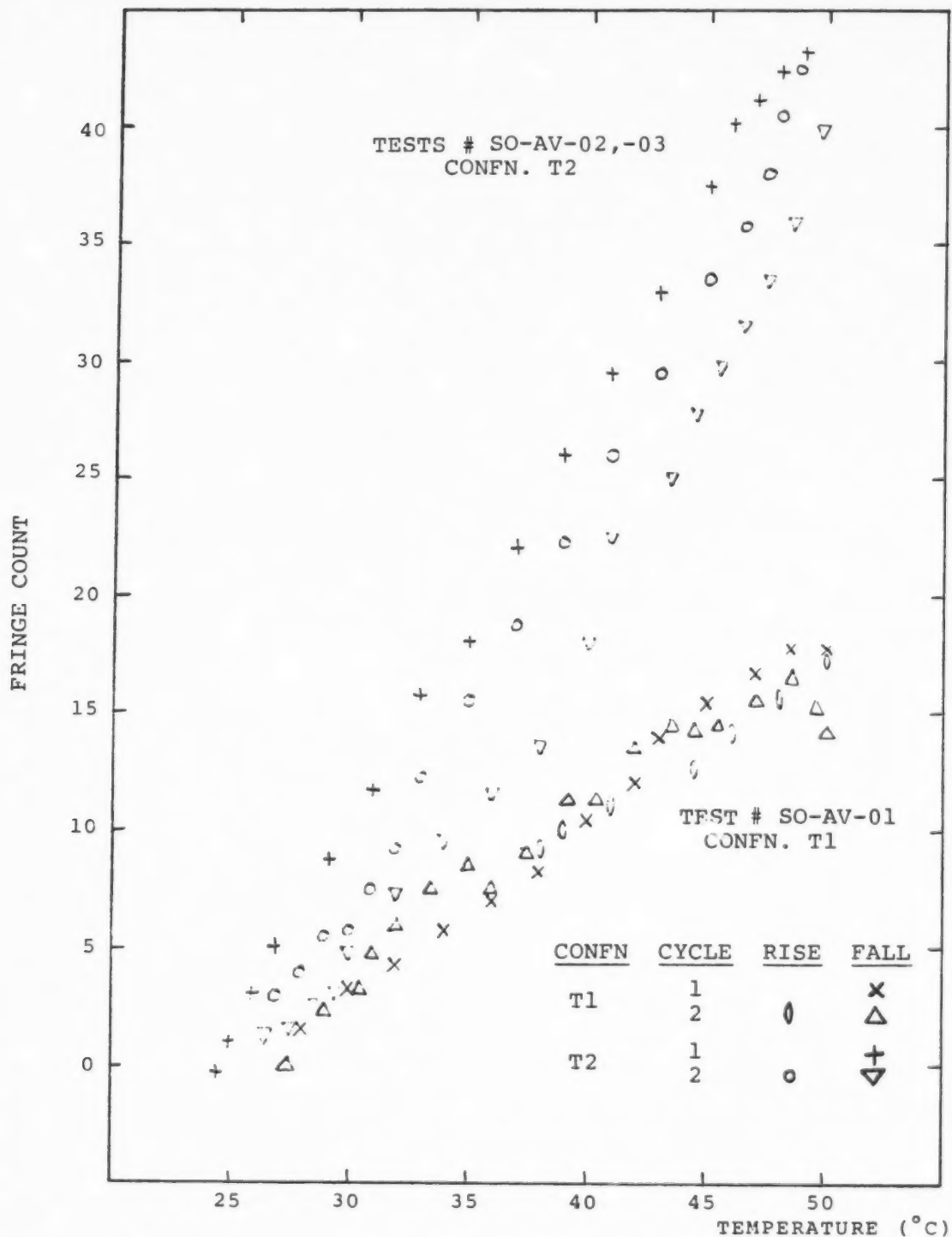


FIGURE D-11 OPTICAL TRANSDUCER OUTPUT
VERSUS AMBIENT TEMPERATURE
- SENSOR AND AXLE CONFIGURATION

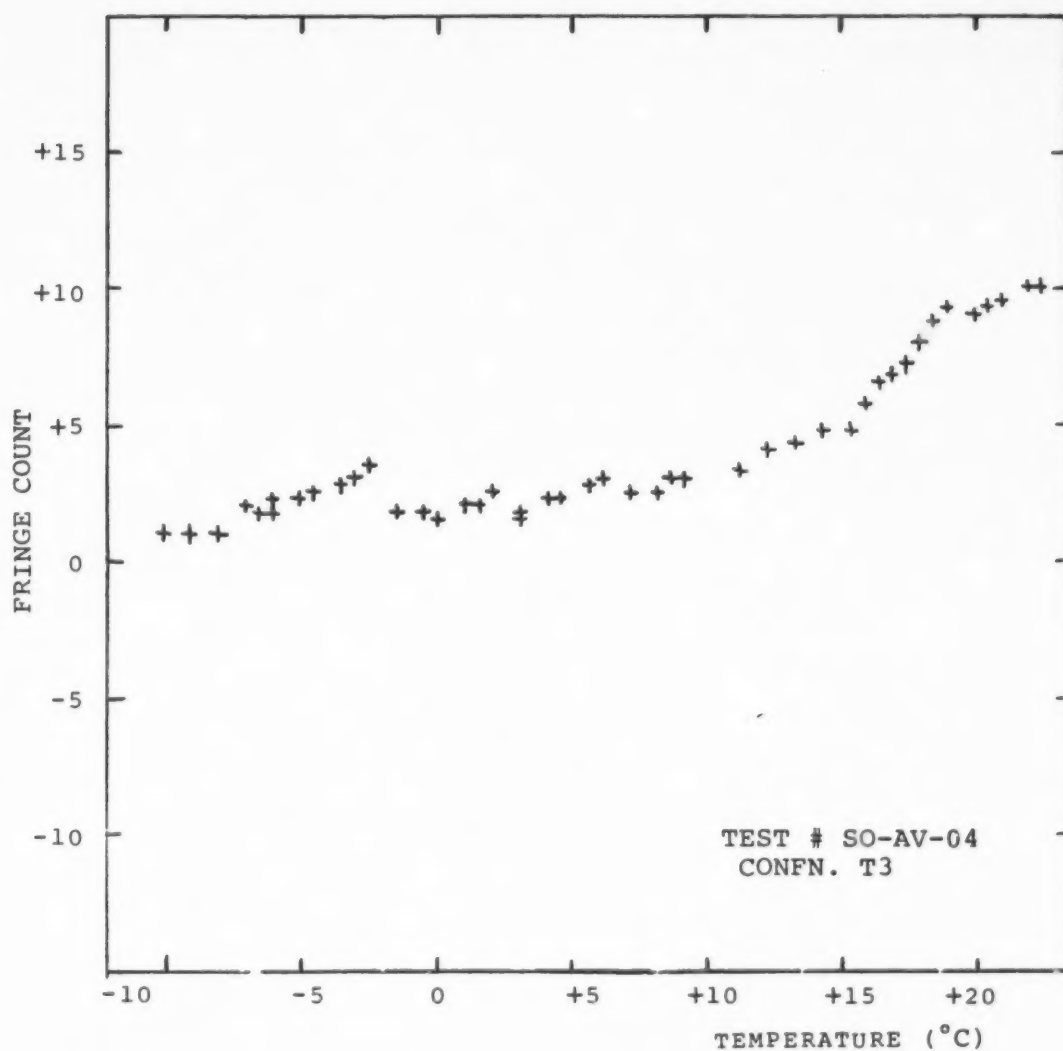


FIGURE D-12 OPTICAL TRANSDUCER OUTPUT VERSUS
AMBIENT TEMPERATURE
- SENSOR ONLY CONFIGURATION

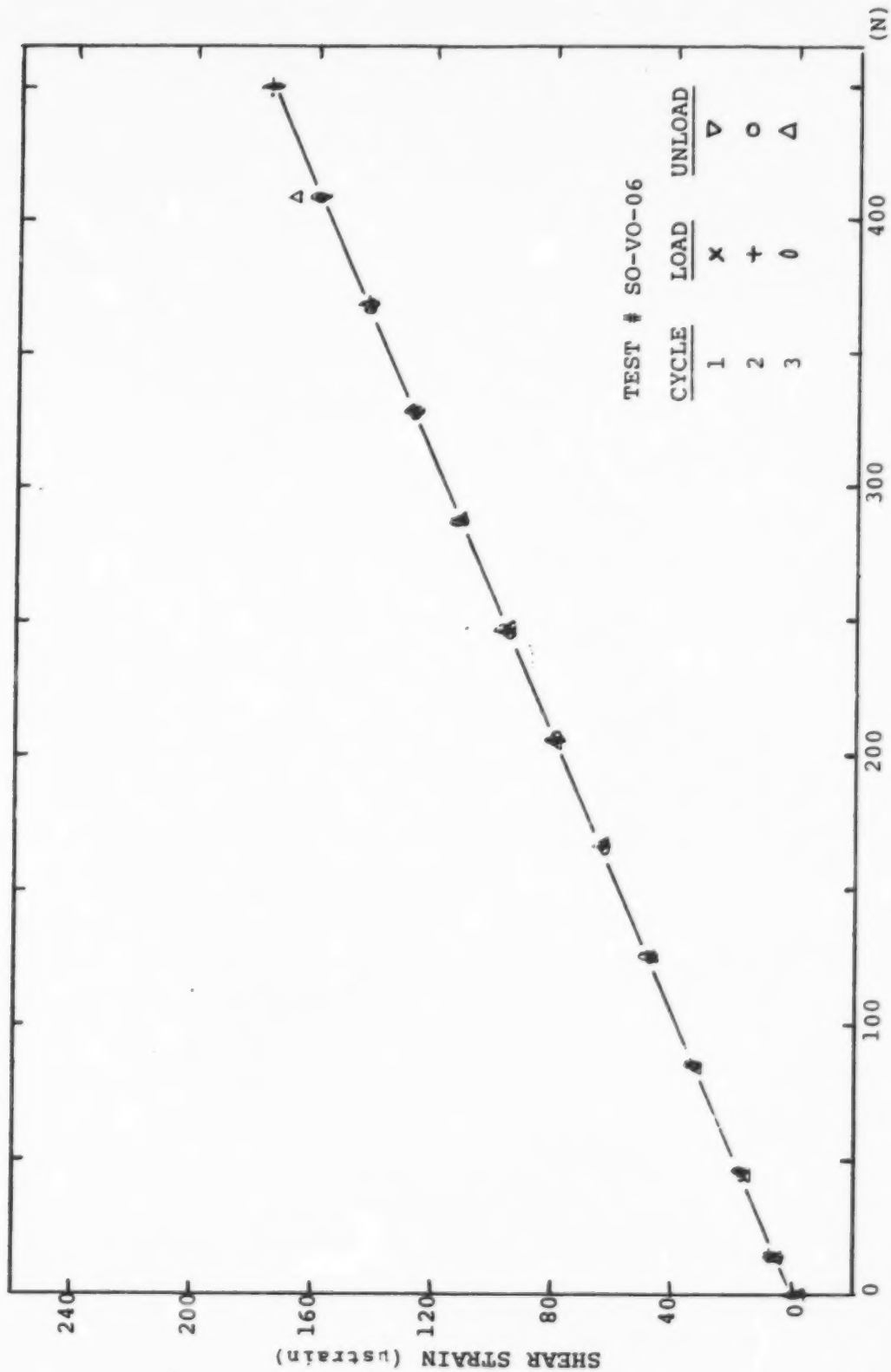


FIGURE D-13 OUTPUT OF SHEAR STRAIN-GAGE VERSUS VERTICAL LOAD
- SENSOR ONLY CONFIGURATION

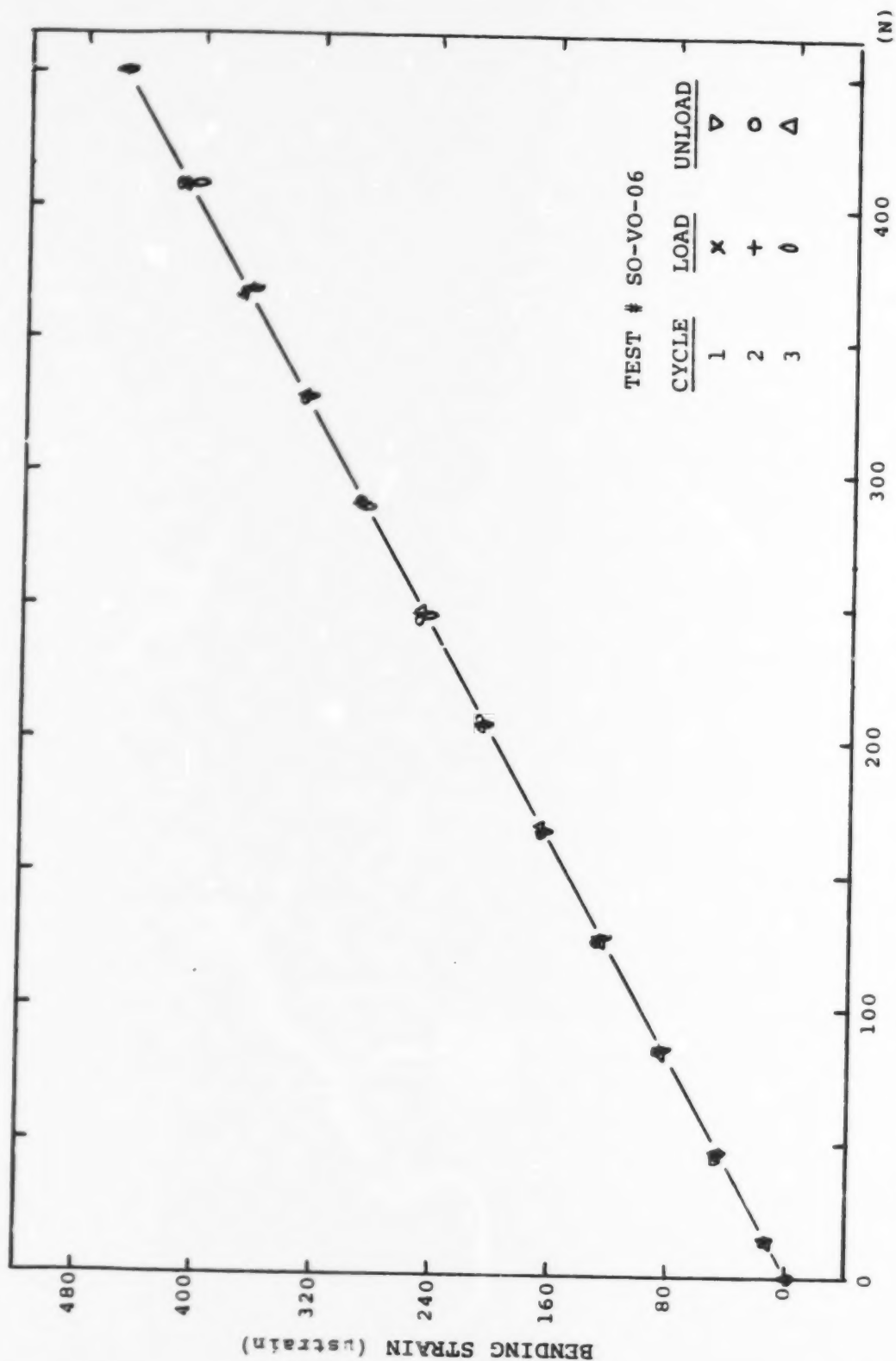


FIGURE D-14 OUTPUT OF BENDING STRAIN-GAGE VERSUS VERTICAL LOAD
- SENSOR ONLY CONFIGURATION

- LOAD CASE - TEST No.		FRINGE COUNT	SHEAR GAUGE (μ strain)	BENDING GAUGE (μ strain)
- VERTICAL 445N - SO-VO-12	Expt	+86.5	+175	+448
	Theory	+90	+173	+437
	Ratio	0.96	1.01	1.03
- LATERAL 196N @ 70mm - SO-HO-03	Expt	-3.2	+1.6	-188
	Theory	+0.1	+0.2	-176
	Ratio	Not Significant	Not Significant	1.07
- LONGITUDINAL 196N - SO-LO-03	Expt	$\approx$ -1.3	+3.4	-4.8
	Theory	0.0	0.0	0.0
	Ratio	N/A	N/A	N/A
- TORSION 85N @ 48mm - SO-TO-02	Expt	-3.25	-3	-7.6
	Theory	0.0	0.0	0.0
	Ratio	N/A	N/A	N/A

note: 1 Newton (N) = 0.225 pound-force (lb)

TABLE D-1 : COMPARISON OF EXPERIMENTAL AND
THEORETICAL TRANSDUCER OUTPUTS
- SENSOR ONLY CONFIGURATION

- LOAD CASE - TEST No.		FRINGE COUNT	SHEAR GAUGE (μ strain)	BENDING GAUGE (μ strain)
- VERTICAL 800N - SA-VO-02	Expt	+44	+93	+96
	Theory	+39	+75	+53
	Ratio	1.13	1.24	1.81
- LATERAL 338N @ 70mm - SA-HO-01	Expt	= +0.5	+2.2	-39
	Theory	+0.6	+1.1	-21
	Ratio	Not Significant	Not Significant	1.86
- LONGITUDINAL 338N - SA-LO-01	Expt	= +1	+6.7	+4.2
	Theory	0.0	0.0	0.0
	Ratio	N/A	N/A	N/A
- TORSION 338N @ 48mm - SA-TO-01	Expt	= +1.25	+4.3	+2.9
	Theory	0.0	0.0	0.0
	Ratio	N/A	N/A	N/A

note: 1 Newton (N) = 0.225 pound-force (lb)

TABLE D-2

: COMPARISON OF EXPERIMENTAL AND
THEORETICAL TRANSDUCER OUTPUTS
- SENSOR AND AXLE CONFIGURATION

POOR

QUALITY

ORIGINAL